The Parameters Determination of Path Loss Model for THz Chip-to-Chip Wireless Communications

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***Abstract*—This paper presents the parameters determination of a path loss model for THz chip-to-chip wireless communication in desktop size metal enclosures. To determine the parameters, gradient decent algorithm was applied to minimize the mean square error between the model and the experimental results. Confirming measurements were performed and the result matches well with the model prediction.**

I. Introduction

For THz wireless channels, several path loss models have been proposed based on the propagation mechanisms. [1]–[5]. Path loss for traveling EM wave in THz band has been modeled as the summation of the spreading loss and the molecular absorption attenuation in [1], [2]. A path loss model which accounts the propagation loss of THz radiation through vegetation has been proposed in [3] by considering the attenuation and scattering effect of the air and leaves. For the wireless channels in indoor environment, the performances of different large-scale path loss models at 30 GHz, 140 GHz, and 300 GHz have been compared in [4]. Unlike the EM wave propagation in free space, THz propagation in metal enclosures experiences both traveling and resonant waves [5]. This yields to larger number of multiple reflections as well as larger multipath spread [5]. Also, due to the resonant nature of the fields, the received power can vary with transceivers positions. Based on these findings, a path loss model in an empty desktop size metal enclosure has been proposed as a function of transceiver's height in [6].

This paper presents the parameters identification of the path loss model discussed in [6]. Considering the cavity effect, the number of dominant resonant modes and their corresponding coefficients are the key parameters required to be determined. To solve this problem, gradient decent algorithm was applied to minimize the mean square error between the model and the experimental results. Measurement results agree well with the prediction which verifies the model.

The remainder of the paper is organized as follows. Section II briefly discusses the path loss model. Section III presents the parameters determination and model verification. Section IV provides concluding remarks.

II. Path Loss Model

A new path loss model for THz chip-to-chip wireless communication inside a desktop size metal cavity has been introduced in [6] with the consideration of propagation loss, cavity effect, and radiation pattern of the antennas being used. The model can be expressed as

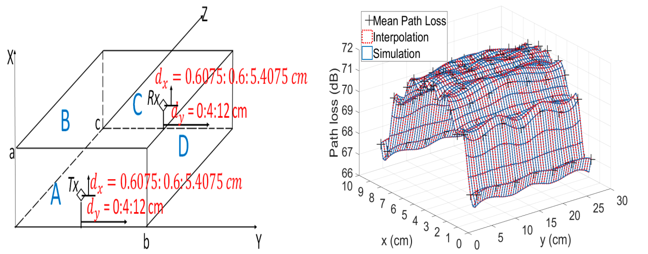
$$\begin{aligned}(PL)_{dB} =& \overline{(PL)^t_{dB}} + 10\log_{10}(|E|^2)^{-1} \\ &+ 10\log_{10}([g(\alpha_t)g(\alpha_r)]^2)^{-1} + X_\sigma, \qquad (1)\end{aligned}$$

where $\overline{(PL)^t_{dB}}$ is the mean path loss of traveling wave, and can be calculated by averaging Friis formula over the available bandwidth of the channel as $\overline{(PL)^t_{dB}} = \frac{1}{BW}\int_{BW}(\frac{4\pi d^{\frac{\gamma}{2}} f}{c_0})^2 df$.

The term $10\log_{10}(|E|^2)^{-1}$ represents the received power variation due to the resonant modes. For only TE modes being considered, the $|E|^2$ can be written as $|E|^2 = \left|\sum_{m=0}^{M}\sum_{n=0}^{N} Ex_{mn}\right|^2 + \left|\sum_{m=0}^{M}\sum_{n=0}^{N} Ey_{mn}\right|^2$, where M and N define the number of dominant TE modes inside the cavity. The expressions of Ex_{mn} and Ey_{mn} can be written as $Ex_{mn} = A_{mn}\cos(\frac{m\pi x}{a})\sin(\frac{n\pi y}{b})$, and $Ey_{mn} = B_{mn}\sin(\frac{m\pi x}{a})\cos(\frac{n\pi y}{b})$, where A_{mn} and B_{mn} are the coefficients for the mode TE_{mn}, and a, b, c are the side lengths of the cavity as shown in Fig. 1a.

The parameter $g(\alpha)$ describes the radiation pattern of the diagonal horn antenna used in our measurements, which can be written as $g(\alpha) = X + Y\cos(Z\alpha)$ [7].

X_σ is the error between the predicted and actual path loss, which can be modeled as a zero-mean Gaussian random variable with standard deviation σ.



(a) (b)

Fig. 1. LoS propagation in an empty metal cavity at 300 GHz: (a) Measurements setup, (b) Comparison of theoretical and measured path loss with respect to x_t/x_r and y_t/y_r.

III. Parameters Determination And Model Verification

To determine the parameters defined in the path loss model, measurements were performed in a metal cavity fabricated with the size of 30.5 cm × 30.5 cm × 10 cm, which approximates the size of a computer desktop casing. The geometry of the metal cavity is shown in Fig. 1a. The phase center's

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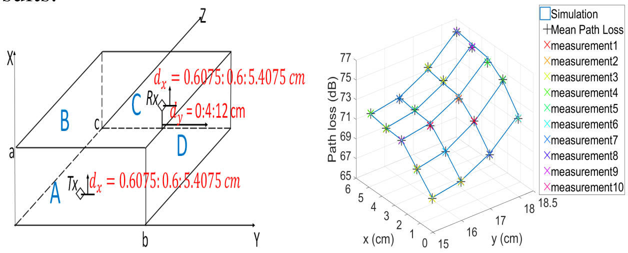
coordinates of Tx and Rx are denoted as (x_t, y_t, z_t) and (x_r, y_r, z_r), respectively. For the measurements, transceivers are moved along x and y direction with fixed z_t and z_r. As shown in Fig. 1a, both Tx and Rx were moved in x direction with $d_x = 0.6075 : 0.6 : 5.4575$ cm and in y direction with $d_y = 0 : 4 : 12$ cm. Since z_t and z_r are fixed, the relative locations of transceivers' phase centers can be specified as $x_t = x_r = dx$, $y_t = y_r = dy + \frac{b}{2}$, $z_t = 0$ cm, and $z_r = 30.5$ cm, where b is the length of the metal cavity which is 30.5 cm. At each location, ten measurements were performed and the results were averaged. To model the path loss variation inside the metal cavity, more measurements in a larger area are required. Since the metal cavity is symmetric, we exploit it to reduce the number of measurements. By doing this, the change of path loss in the area where x_t/x_r varies from 0.6075 to 9.3725 cm and y_t/y_r varies from 3.25 to 27.25 cm can be estimated. By interpolating the results, 1519 samples were available to determine the parameters M, N, A_{mn}, and B_{mn}. These samples were ordered as $PL_i : 1 \leq i \leq 1519$ based on the corresponding locations of the Rx, (x_{ri}, y_{ri}). Since only LoS propagation was considered in the measurements, $g(\alpha) = 1, X_\sigma = 0$, the power contributed by the resonant modes $|E_i|$ can be calculated with equation (1) for any given γ.

We first define $\mathbf{X_1} = [A_{01}, A_{02}, \cdots, A_{MN}]^T$, $\mathbf{X_2} = [B_{01}, B_{02}, \cdots, B_{MN}]^T$, and $\mathbf{X} = [\mathbf{X_1}^T, \mathbf{X_2}^T]^T$. Also, we can assume $\mathbf{a_i} = [\cos(\frac{0 \cdot \pi x_{ri}}{a}) \sin(\frac{\pi x_{ri}}{b}), \cdots, \cos(\frac{M \cdot \pi x_{ri}}{a}) \sin(\frac{N \cdot \pi x_{ri}}{b}), 0, \cdots, 0]^T$ and $\mathbf{b_i} = [\sin(\frac{0 \cdot \pi x_{ri}}{a}) \cos(\frac{\pi x_{ri}}{b}), \cdots, \sin(\frac{M \cdot \pi x_{ri}}{a}) \cos(\frac{N \cdot \pi x_{ri}}{b}), 0, \cdots, 0]^T$. Both $\mathbf{X}$, $\mathbf{a_i}$, and $\mathbf{b_i}$ have the length of $2[(M+1)(N+1)-1]$. Since $|E|^2 = |E_x|^2 + |E_y|^2 = |\mathbf{a_i}^H \mathbf{X}|^2 + |\mathbf{b_i}^H \mathbf{X}|^2$, the problem can be simplified as

$$\begin{aligned}
&\min_{\mathbf{X}} \sum_{i=1} \left(|\mathbf{a_i}^H \mathbf{X}|^2 + |\mathbf{b_i}^H \mathbf{X}|^2 - |E_i|^2 \right)^2 \\
&= \min_{\mathbf{X}} \sum_{i=1} \left(\mathbf{X}^H (\mathbf{a_i} \mathbf{a_i}^H + \mathbf{b_i} \mathbf{b_i}^H) \mathbf{X} - |E_i|^2 \right)^2 \\
&= \min_{\mathbf{X}} \sum_{i=1} \left(\mathbf{X}^H \mathbf{V_i} \mathbf{X} - |E_i|^2 \right)^2 \qquad (2)
\end{aligned}$$

for any given M, N, and γ, where $(\bullet)^H$ is the Hermitian operator. This problem can be solved with gradient decent. The gradient $\Delta \mathbf{X}$ can be calculated as $\Delta \mathbf{X} = \frac{\partial \sum_{i=1} (\mathbf{X}^H \mathbf{V_i} \mathbf{X} - |E_i|^2)^2}{\partial \mathbf{X}} = 4 \sum_{i=1} \left(\mathbf{X}^H \mathbf{V_i} \mathbf{X} - |E_i|^2 \right) \mathbf{V_i} \mathbf{X}$. The global minimum can be gradually approached with $\mathbf{X}_{k+1} = \mathbf{X}_k - \mu \Delta \mathbf{X}_k$, where μ represents the step size which is a small number. To shrink the processing time, we applied the Nesterov's accelerated gradient algorithm to first reach the area where the global minimum is, and then gradually approach it. By iterating the process with different M, N, and γ, parameters M and N that define the dominant modes inside the cavity are determined to be 25 and 13, respectively, the path loss exponent γ is estimated to be 1.9995. Also, the coefficients A_{mn} and B_{mn} are estimated for each mode. The model was compared with the mean value of measured results at each location after flipping and interpolating in Fig. 1b. As shown in the figure, the model matches well with the measured results.



(a) (b)

Fig. 2. LoS propagation in an empty metal cavity at 300 GHz with a misalignment between Tx and Rx: (a) Measurements setup, (b) Comparison of theoretical and measured path loss with respect to h_r.

To verify the model, measurements have been done with the consideration of the misalignment between Tx and Rx. As shown in Fig. 2a, measurements were performed with both Tx and Rx being moved vertically with x_t/x_r varying from 0.6075 to 5.4075 cm with the step size of 1.2 cm. At each height, Rx was moved in y direction with y_r varying from 15.25 to 18.25 cm with the step size of 1 cm. At each location, measurements were repeated 10 times. Based on the difference between y_t and y_r at each location, path loss can be estimated with the calculated parameters A_{mn}, B_{mn}, and γ. A good agreement between the model prediction and the measured results can be observed from Fig. 2b.

IV. Conclusions

This paper presents a path loss model for THz chip-to-chip wireless communication in desktop size metal enclosures and its parameters identification. To determine the parameters' values, gradient decent algorithm was applied to minimize the mean square error between the calculation and the experimental results. Measurements were performed to verify the correctness of the model. A good agreement between the measured and simulated results was observed.

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