Research Paper Presentation

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Title and Authors

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Wide-band Channel Measurements and Temporal-Spatial Analysis for Terahertz Indoor Communications

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Abstract

1. Terahertz communications are envisioned as a key technology for beyond 5G wireless systems, owing to its unprecedented multi-GHz bandwidth.
2. A wide-band channel measurement between 130 GHz and 143 GHz is investigated in a typical meeting room.
3. Physical parameters and insights in the THz indoor channel are comprehensively analyzed to find correlations among THz multipath characteristics.

Introduction

1. There has been an exponential growth in wireless data traffic recently which demands for high-speed wireless communication.
2. The Terahertz (THz) (0.1-10 THz) band is capable of providing dozens and hundreds of gigahertz (GHz) continuous spectrum bands. Specifically, 140 GHz band is the first spectral window to penetrate into the THz band.
3. One challenge is to measure, analyze, and model the THz electromagnetic wave propagation and channel characteristics.

Concepts

Bragg's Law

Bragg's law provides the condition for a plane wave to be diffracted by a family of lattice planes:

$$2d \sin\theta = n\lambda$$

where n is an integer representing order of reflection, λ is the wavelength, d is the vector representing the displacement between reflection sites, θ is the angle between the reflected ray and the plane formed by the material's surface.
Waves reflected through an angle corresponding to n = 1 are said to be in the first order of reflection; the angle corresponding to n = 2 is the second order, and so on.

Concepts

Complementary Error Function

The complementary error function of x is defined as:

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2}\,dt \tag{1}$$

$$= 1 - erf(x) \tag{2}$$

Abbreviations

Abbreviation	Meaning
THz	TeraHertz
Tx	Transmitter
Rx	Receiver
MPCs	Multi-Path Components
VNA	Vector Network Analyzer
HPBW	Half-Power BeamWidth
FSPL	Free Space Path Loss
LoS	Line of Sight
NLoS	Non Line of Sight
PDAP	Power-Delay-Angular Profiles

Table: Abbreviations used in presentation

Experimental Setup

1. The experiment was conducted in a typical meeting room of dimensions 10.15 m $\times$ 7.9 m $\times$ 4 m.
2. A 4.8 m $\times$ 1.9 m $\times$ 0.77 m desk is placed in the center, and a number of chairs are placed around the desk.
3. Two TVs are closely placed and parallel to a wall.
4. The material of one wall is glass, while the other three walls are lime walls.
5. With a fixed Tx, multipath measurements are conducted at ten different receiver positions. Directional antennas are equipped at Tx and Rx to resolve MPCs in the angular domain.

Machinery Setup

1. The measurement platform consists of a 140 GHz transmission system and a VNA.
2. The signal produced by VNA is up-converted to the frequency band from 130 to 140 GHz.
3. The antennas at Tx and Rx are horn antennas.
4. Tx produces an antenna gain of 15 dBi with the HPBW of 30° at 140 GHz.
5. Rx produces an antenna gain of 25 dBi with the HPBW of 10° at 140 GHz.
6. The two antennas are mounted on two rotation units and rotated by step motors, respectively.

Table of known parameters

Parameter	Symbol	Value
Start frequency	f_{start}	130GHz
End frequency	f_{end}	140GHz
Bandwidth	B_w	13GHz
Sampling points	N	1301
Sampling Interval	Δf	10MHz
Average noise floor	P_N	-120 dBm
Test signal power	P_{in}	1mW
HPBW of transmitter	$HPBW^{Tx}$	30°
HPBW of receiver	$HPBW^{Rx}$	10°
Antenna gain at Tx	G_t	15dBi
Antenna gain at Rx	G_r	25dBi
Time domain resolution	Δt	76.9ps
Path length resolution	ΔL	2.3cm
Maximum excess delay	τ_m	100ns
Maximum path length	L_m	30m

Table: Known measurement parameters

Image of setup

Figure: Meeting Room

Image of setup plan

Figure: Meeting Room Layout

Calibration

The S21 parameter for calibration, denoted by S_{21}^{cal} is given by:

$$S_{21}^{cal} = H_{sys} \times H_{att}$$

where H_{att} is the channel transfer function of the THz attenuator which replaces the antennas connected to Tx and Rx; H_{sys} is the channel transfer function of the measurement system. The path loss of an LoS path is the negative number of its S21 parameter averaged over the measurement spectrum band. The obtained values are then compared with the FSPL calculated by Friss' Law,

$$FSPL[dB] = -20 \log_{10} \left(\frac{c}{4\pi f d} \right)$$

where c denotes the light speed, f is the carrier frequency and d is the separation distance between Tx and Rx.

Calibration Results

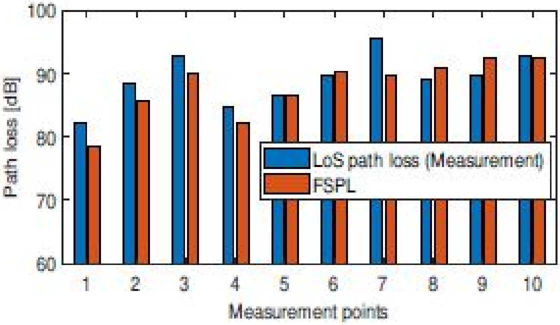

Figure: Comparison between measured LoS path loss and FSPL

By comparison, we observe the measured path loss coincides with the FSPL computation having an average deviation of 2 dB indicating a successful calibration.

Path Loss

Path loss is defined as the transmit power divided by received power and is typically characterized in decibel scales as:

$$L = l_0 + 10n\log_{10} D + S \tag{3}$$

where l_0 is the path loss at a reference distance d_0 (typically 1m), n is the path loss exponent, D is the transmitter-receiver separation and S is the shadowing (noise), known as Log-normal, $S \sim N(0, \sigma_s^2)$.

PDF of Path loss in a square region

Let us normalize L as:

$$U = \frac{L - l_0}{\sigma_s} = \frac{10n\log_{10} D}{\sigma_s} + \frac{S}{\sigma_s} \tag{4}$$

Then, the normalized shadowing parameter is $\frac{S}{\sigma_s} \sim N(0,1)$. Let (X_1, Y_1) and (X_2, Y_2) represent a pair of transmitter and receiver. Then,

$$D = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2} \tag{5}$$

$$f_D(d) = \begin{cases} \frac{2d^3}{a^4} + \frac{8d^2}{a^3} + \frac{2\pi d}{a^2} & 0 \le d < a \\ -\frac{2d^3}{a^4} + \left(-\frac{4}{a^2} + \frac{8\arcsin(\frac{a}{d})}{a^2} + \frac{8\sqrt{d^2-a^2}}{a^3} - \frac{2\pi}{a^2}\right) & a \le d \le \sqrt{2}a \end{cases} \tag{6}$$

$$\approx \begin{cases} \frac{2d^3}{a^4} + \frac{8d^2}{a^3} + \frac{2\pi d}{a^2} & 0 \le d < a \\ \frac{-8(d-\sqrt{2}a)^3}{3a^4} & a \le d \le \sqrt{2}a \end{cases} \tag{7}$$

PDFs

Let

$$Y = \frac{10n\log_{10}(D)}{\sigma_s} \tag{8}$$

Then, the PDF of Y can be transformed from equation (7) as

$$f_Y(y) = \begin{cases} \frac{2\xi e^{4\xi y}}{a^4} - \frac{8\xi e^{3\xi y}}{a^3} + \frac{2\pi\xi e^{2\xi}}{a^2} & -\infty < y < \frac{\ln a}{\xi} \\ -\frac{8\xi e^{4\xi y}}{3a^4} + \frac{8\sqrt{2}\xi e^{3\xi y}}{a^3} - \frac{16\xi e^{2\xi y}}{a^2} + \frac{16\sqrt{2}\xi e^{\xi y}}{3a} & \frac{\ln a}{\xi} \leq y \leq \frac{\ln(\sqrt{2}a)}{\xi} \end{cases} \tag{9}$$

where $\xi = \frac{\ln(10)\sigma_s}{10n}$.

PDF of U

Furthermore, as S and D are independent, the PDF of U is the convolution integration of $f_Y(y)$ with the Gaussian normal function:

$$f_U(u) = \int_{-\infty}^{\infty} f_Y(y) \frac{1}{\sqrt{2}\pi} \exp\left(-\frac{(u-y)^2}{2}\right) dy \tag{10}$$

$$\begin{aligned} f_U(u) = &\left(\frac{\xi \pi e^{2\xi u + 2\xi^2}}{a^2} - \frac{4\xi e^{3\xi u + \frac{9}{2}\xi^2}}{a^3} + \frac{\xi e^{4\xi u + 8\xi^2}}{a^4}\right) \times \\ &\operatorname{erfc}\left(\frac{\xi u - \ln a + 2\xi^2}{\sqrt{2}\xi}\right) \\ &+ \left(\operatorname{erfc}\left(\frac{\xi u - \ln(\sqrt{2}a) + 2\xi^2}{\sqrt{2}\xi}\right) - \operatorname{erfc}\left(\frac{\xi u - \ln a + 2\xi^2}{\sqrt{2}\xi}\right)\right) \times \\ &\left(-\frac{4\xi e^{4\xi u + 8\xi^2}}{3a^4} + \frac{4\sqrt{2}\xi e^{3\xi u + \frac{9}{2}\xi^2}}{a^3} - \frac{8\xi e^{2\xi u + 2\xi^2}}{a^2} + \frac{8\sqrt{2}\xi e^{\xi u + \frac{1}{2}\xi^2}}{3a}\right) \end{aligned} \tag{11}$$

for $u \leq \frac{\ln(\sqrt{2}a)}{\xi} + 3$ where erfc(.) is the complementary error function.

PDF and CDF of L

Finally, the PDF of L is transformed from equation (11) as:

$$f_L(l) = \frac{1}{\sigma_s} f_U\left(\frac{l - l_0}{\sigma_s}\right) \tag{12}$$

for $l \leq l_0 + \frac{\sigma_s \ln(\sqrt{2}a)}{\xi} + 3\sigma_s$. The CDF can also be explicitly given, but the resulting formula is too lengthy and complex. Instead, the CDF when plotted for discrete values looks like:

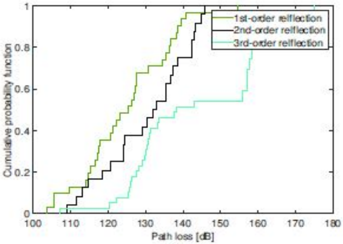

Figure: CDF of reflected paths

Reflection List

RX	Number of MPCs	1st-order reflection		2nd-order reflection		3rd-order reflection		$\frac{P_{Wall}}{P_{Obstacle}}$
		Wall	Obstacle	Wall	Obstacle	Wall	Obstacle	
1	8	1	3	2	0	2	0	1.10
2	11	3	1	4	1	2	0	9.08
3	11	3	3	4	0	1	0	9.08
4	14	3	3	3	1	3	1	8.14
6	8	3	0	3	0	1	1	618.65
7	8	2	0	2	0	2	2	13.13
8	6	2	0	1	1	2	0	9.58
9	5	2	0	1	0	2	0	inf
10	5	2	0	1	0	0	2	0.95

Table: Reflections of MPCs for all the receivers

Multipath PDAPs

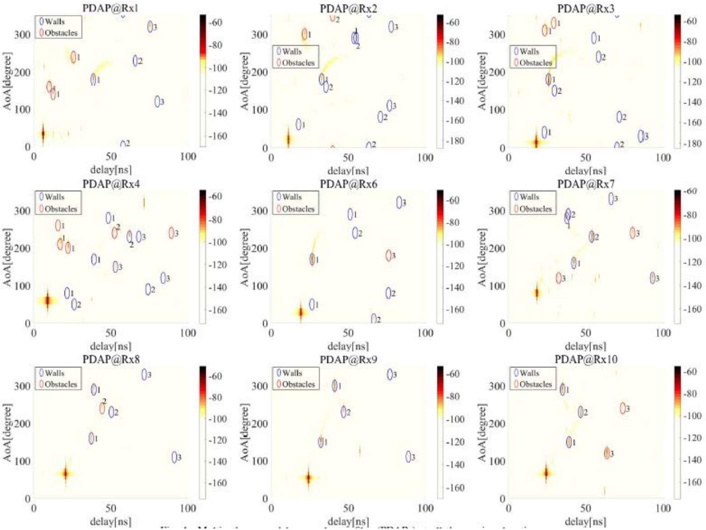

Figure: Multipath PDAPs at all receivers

Temporal and Spatial features

1. K-factor: Defined as the ratio between the power of the LoS path and the power of the remaining NLoS MPCs.
2. RMS Delayspread (DS) =

$$\tau_{rms} = \sqrt{\left(\frac{\int_0^\infty (\tau - \overline{\tau})^2 A_c(\tau)\, d\tau}{\int_0^\infty A_c(\tau)\, d\tau}\right)} \tag{13}$$

$$\text{with } \overline{\tau} = \frac{\int_0^\infty \tau A_c(\tau)\, d\tau}{\int_0^\infty A_c(\tau)\, d\tau} \tag{14}$$

   where $A_c(\tau)$ denotes the power angular profile.
3. Angular spread (AS) can be modelled as:

$$\sigma_{\varphi/\theta}(d^2) = a \times d^2 + bd + c + \chi_\sigma \tag{15}$$

   where χ_σ denotes a zero mean Gaussian random variable with the standard deviation σ, accounting for the deviations of the individual spreads from the polynomial function.

Statistics

RX	Distance [m]	K-factor [dB]	DS [ns]	AS [°]
1	1.43	39.57	3.58	25.23
2	3.16	29.07	1.9	20.45
3	5.26	26.14	2.95	33.97
4	2.20	26.65	5.72	20.95
6	5.52	15.96	1.17	26.27
7	5.14	20.07	10.02	39.23
8	5.87	20.38	1.62	16.67
9	6.97	12.60	3.95	29.12
10	7.12	12.40	5.87	31.54

Table: Statistics of MPCs for each receiver

Correlation Matrix

A correlation matrix is a table showing correlation coefficients between variables. Each cell in the table shows the correlation between two variables. Let r_{jk} be the correlation coefficient between variables x_j and x_k.

$$r_{jk} = \frac{\sum_{i=1}^{n}(x_{ij} - \overline{x_j})(x_{ik} - \overline{x_k})}{\sqrt{\sum_{i=1}^{n}(x_{ij} - \overline{x_j})^2}\sqrt{\sum_{i=1}^{n}(x_{ik} - \overline{x_k})^2}} \tag{16}$$

$$Cor(x_j, x_k) = \frac{\sum_{i=1}^{n}(x_{ij} - \overline{x_j})(x_{ik} - \overline{x_k})}{\sqrt{\sum_{i=1}^{n}(x_{ij} - \overline{x_j})^2}\sqrt{\sum_{i=1}^{n}(x_{ik} - \overline{x_k})^2}} \tag{17}$$

$$= \begin{cases} 1 & \text{if } j = k \\ r_{jk} & \text{if } j \neq k \end{cases} \tag{18}$$

Correlation Matrix

The correlation matrix for the characteristics is:

	d	N	K	DS	AS	$\frac{P_{Wall}}{P_{Obstacle}}$
Distance	1.00	-	-	-	-	-
Number of MPCs	-0.70	1.00	-	-	-	-
K-factor	-0.67	0.02	1.00	-	-	-
Delay Spread	0.04	0.00	-0.09	1.00	-	-
Angular Spread	0.37	-0.20	-0.13	0.66	1.00	-
$\frac{P_{Wall}}{P_{Obstacle}}$	0.41	-0.42	-0.15	-0.02	0.11	1.00

Table: Correlation matrix among THz multipath characteristics

Conclusions

1. The THz indoor channel is sparse in both temporal and spatial domains, while the number of MPCs is less than 10.
2. Although the transmitter directs a narrow beam to the receiver, the existence of MPCs is still not negligible, especially when receivers are far from Tx.
3. Wall-reflected MPCs contain considerably higher power than other obstacle-reflected MPCs in THz indoor environment.
4. A longer communication distance might cause a high sparsity, smaller K-factor, broader angular spread, and stronger wall-reflected power.