Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Terahertz Channel Measurement and Characterization on a Desktop from 75 to 400 GHz

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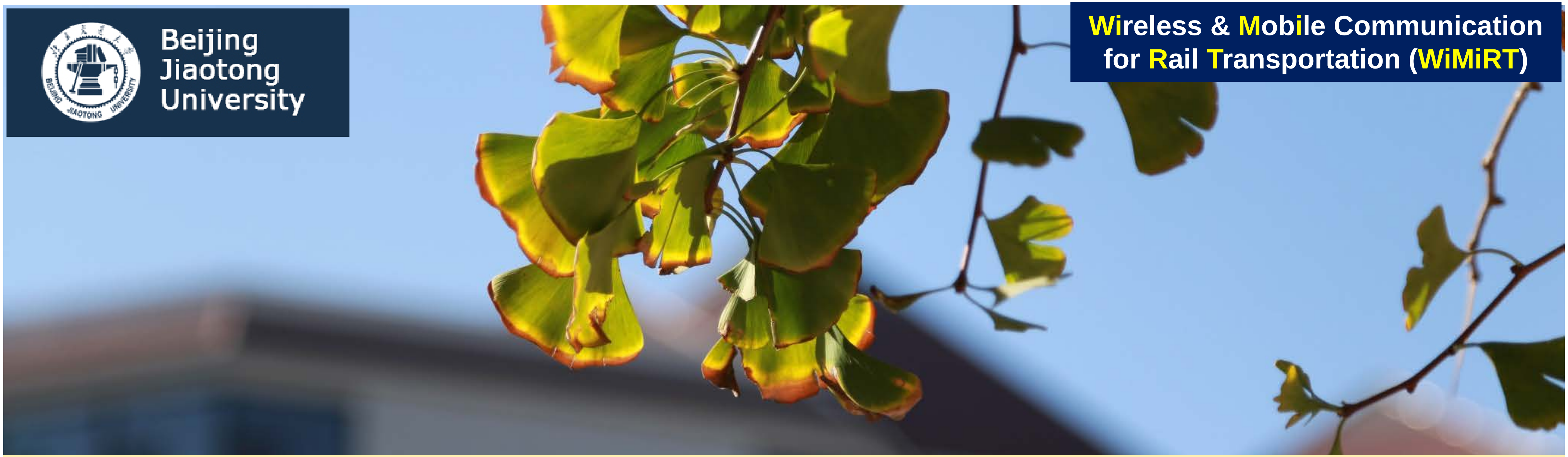
Re: n/a

Abstract: The emerging technology terahertz (THz) communication is envisioned to provide high-data-rate wireless links. The wide swath of the unused and unexplored spectrum makes it a significant candidate for the sixth-generation mobile communications (6G). In this proposal, a series of channel measurements are conducted on an optical table to characterize the wireless channel on a desktop. The measured frequency range is from 75 GHz to 400 GHz, which has covered the main band planed for 6G within THz band. Eight frequency bands with ultrawide bandwidth are measured dividually in order to explore how the channel characteristics change along with frequency. By comparison of the power delay profiles (PDPs) between measurements and ray-tracing (RT) simulations, the measured multipaths can be physically interpreted. Moreover, with the aid of this self-developed RT simulator, electromagnetic (EM) property of the painted metal (which is the relevant material generating multi-order reflected paths in the measurements) is extracted, finding that the imaginary part of the relative permittivity is considerably small compared to the perfect conductor because of the painting. The key channel parameters, in terms of root-mean-square (RMS) delay spread and Ricain K-factor, are analyzed and modeled with frequency. Last but not least, in order to describe the channel characteristics in the presence of obstruction, we measure the penetration loss for several common materials (glass, hardboard, wood, plastic, and potted plant). As expected, the penetration loss increases with the increase of frequency for all tested samples.

Purpose: Information of IEEE 802.15 SC THz



Terahertz Channel Measurement and Characterization on a Desktop from 75 to 400 GHz

Haofan Yi [1,2], Ke Guan [1,2], Danping He [1,2], Bo Ai [1,2], Jiaowu Dou[3,4], Fusheng Zhu[5], Bin Lu[6] and Zhangdui Zhong[1,2]

[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, [2] Frontiers Science Center for Smart High-speed Railway System, [3]State Key Laboratory of Mobile Network and Mobile Multimedia Technology, [4]ZTE Corporation, [5]Guangdong Communications & Networks Institute, [6]China Telecom Research Institute

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Outline

- Motivation
- THz Channel Measurement on a Desktop
  - Measurement Campaign
  - Channel Characterization and Analysis
- Penetration Loss Measurement
  - Measurement Campaign
  - Numerical Results and Analysis
- Conclusion and Future Work

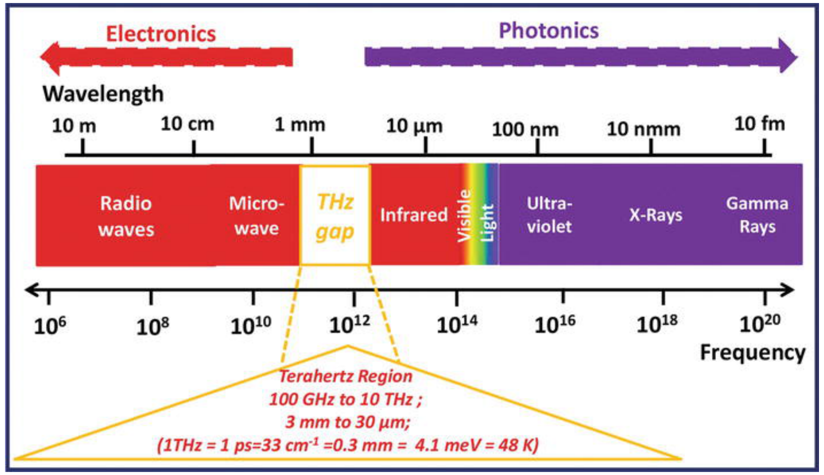
Motivation

Shannon information theory

$$C = B\log_2(1+S/N)$$

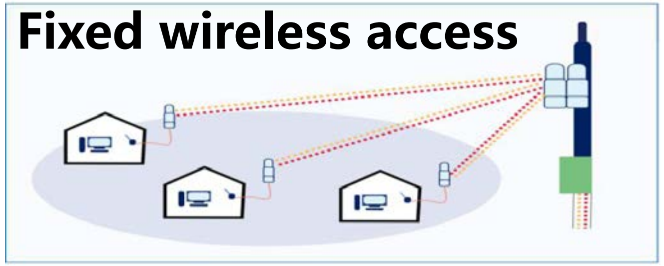
One of the most effective ways to increase the data rate:

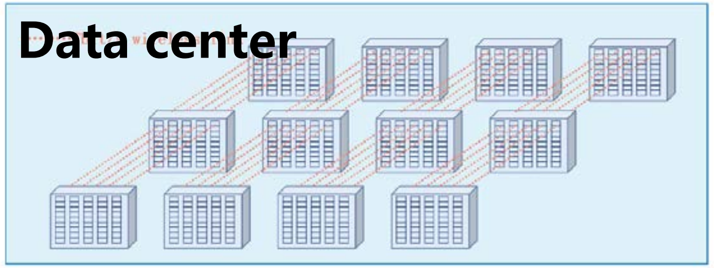
Expand the communication bandwidth

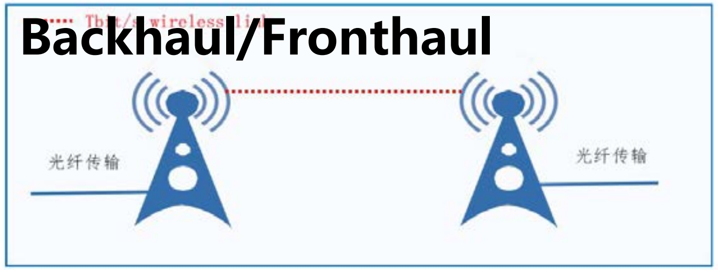


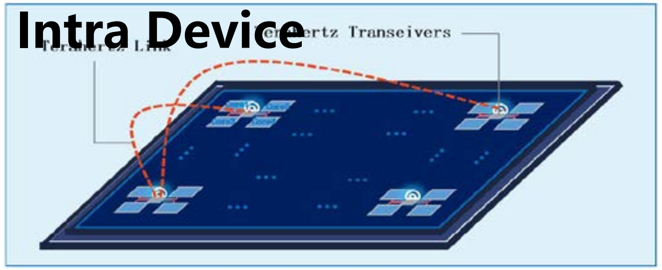
Terahertz communication (100 GHz-10 THz): the bandwidth can reach **tens of GHz**, which is more than 10 times that of 5G millimeter wave, and is **one of the key technologies of 6G**.

IEEE Std 802.15.3d









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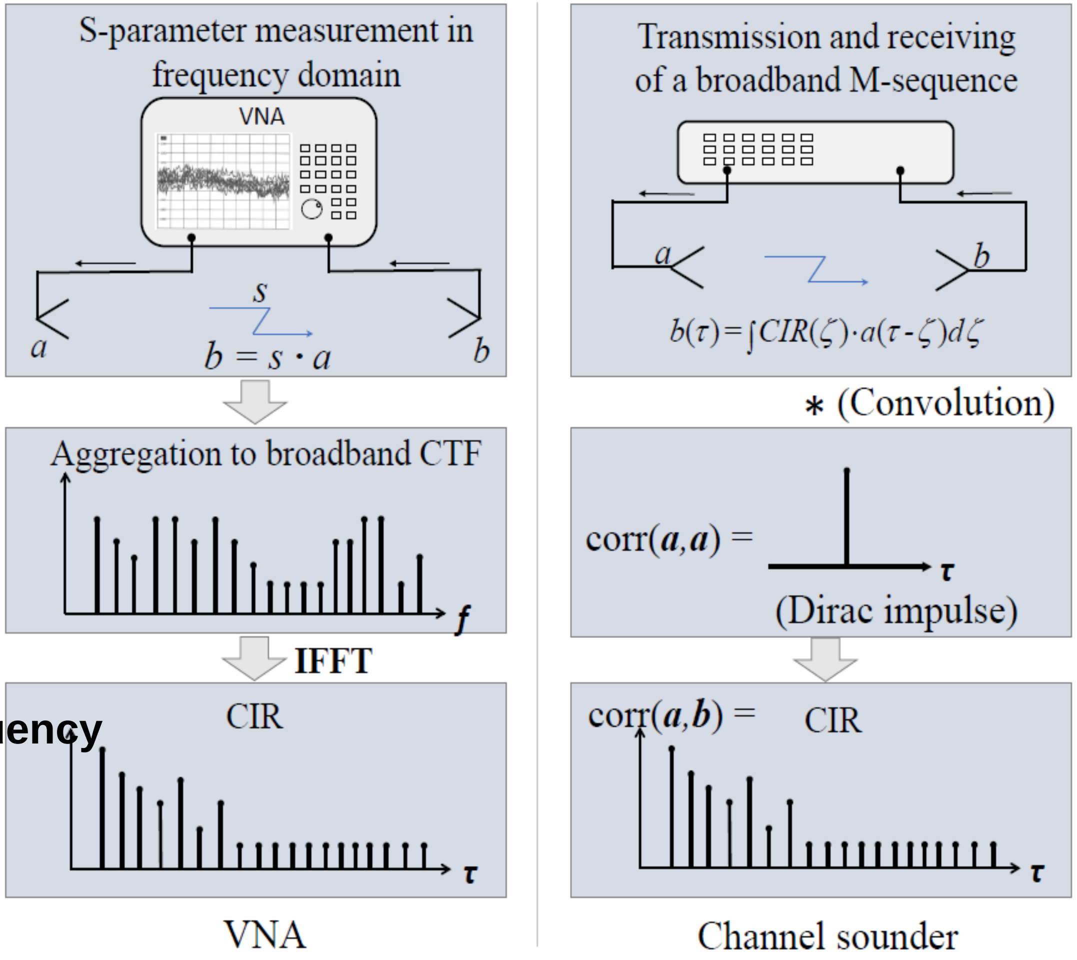
Measurement Campaign

Measurement Methodology

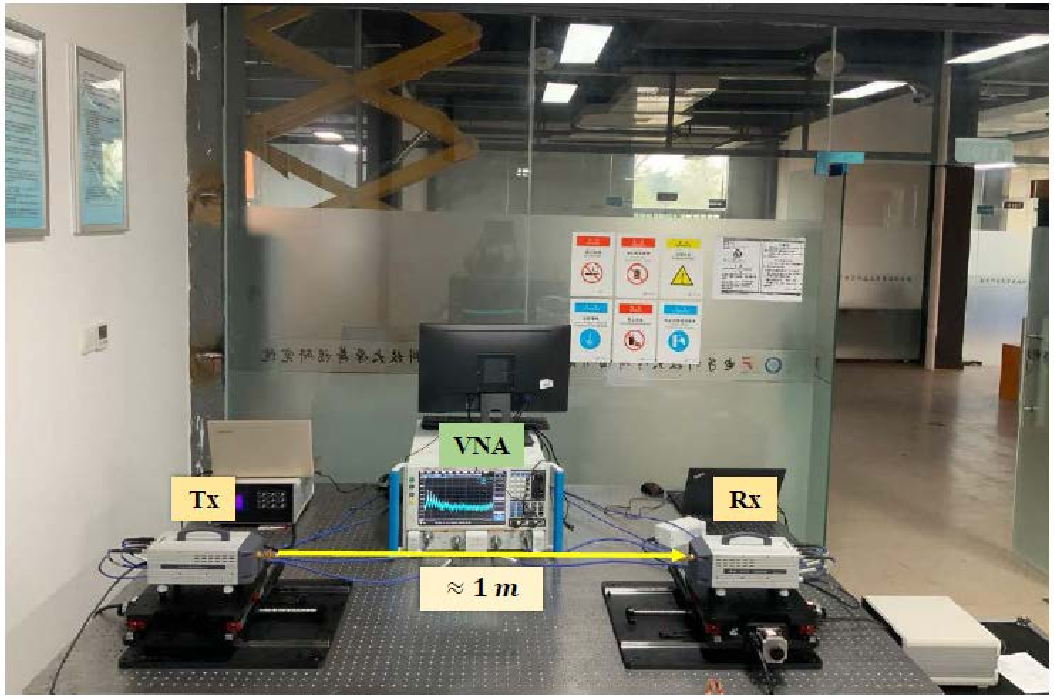
- **VNA-based measurement**
  - In frequency domain
  - CIR ->by IFFT from CTF
  - Pros: accurate broadband system;
    large dynamic range.
  - Cons: long time-consuming;
    cannot capture the dynamic
    channel variations.
- **Channel sounder methodology**
  - In time domain
  - CIR-> Correlation function of M-sequency
  - Pros: dynamic measurement
  - Cons: small dynamic range



Measurement Campaign

VNA-based Measurement

Measurement Scenario

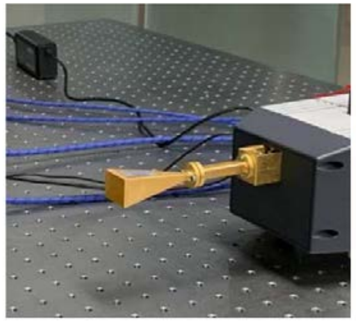


Calibration method：

SOLT **S**hort-**O**pen-**L**oad-**T**hru

Antenna

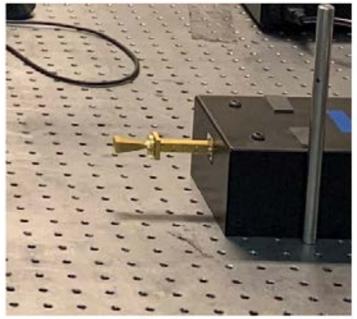
WR-10 WR-6.5



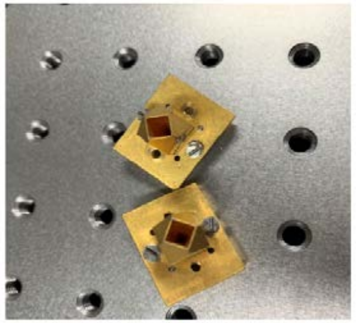
(a) 75-110 GHz

(b) 110-170 GHz

WR-5.1 WR-2.8



(c) 180-220 GHz



(d) 260-400 GHz

Measurement Campaign

System Parameters

The temporal resolution

$$\tau_{res} = \frac{1}{BW}$$

The spatial resolution

$$D_{res} = \frac{c}{BW}$$

The maximum excess delay

$$\tau_{max} = \frac{1}{\Delta f}$$

The maximum detected path length

$$D_{max} = \frac{c}{\Delta f}$$

Measurement Configurations

Parameter	Symbol	Value	Value	Value	Value
Start frequency	f_{start} [GHz]	75	110	140	180
End frequency	f_{end} [GHz]	110	140	170	220
Bandwidth	BW [GHz]	35	30	30	40
Number of frequency points	N	5001	5001	5001	4001
Sampling interval	Δf [MHz]	7	6	6	10
IF frequency bandwidth	IFBW [kHz]	1	1	1	1
Temporal resolution	τ_{res} [ns]	0.029	0.033	0.033	0.025
Spatial resolution	D_{res} [cm]	0.87	0.99	0.99	0.75
Maximum excess delay	τ_{max}[ns]	142.9	166.7	166.7	100.0
Maximum path length	D_{max} [m]	42.9	50.0	50.0	30.0
Distance between Tx and Rx	d [m]	1.0	1.0	1.0	0.8

Parameter	Symbol	Value	Value	Value	Value
Start frequency	f_{start} [GHz]	260	295	330	365
End frequency	f_{end} [GHz]	295	330	365	400
Bandwidth	BW [GHz]	35	35	35	35
Number of frequency points	N	5001	5001	5001	5001
Sampling interval	Δf [MHz]	7	7	7	7
IF frequency bandwidth	IFBW [kHz]	1	1	1	1
Temporal resolution	τ_{res} [ns]	0.029	0.029	0.029	0.029
Spatial resolution	D_{res} [cm]	0.87	0.87	0.87	0.87
Maximum excess delay	τ_{max}[ns]	142.9	142.9	142.9	142.9
Maximum path length	D_{max} [m]	42.9	42.9	42.9	42.9
Distance between Tx and Rx	d [m]	1.0	1.0	1.0	1.0

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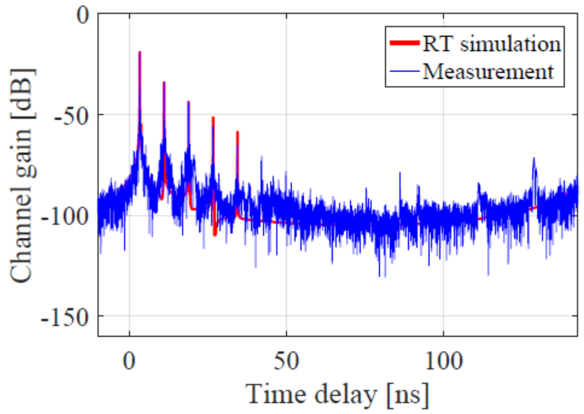
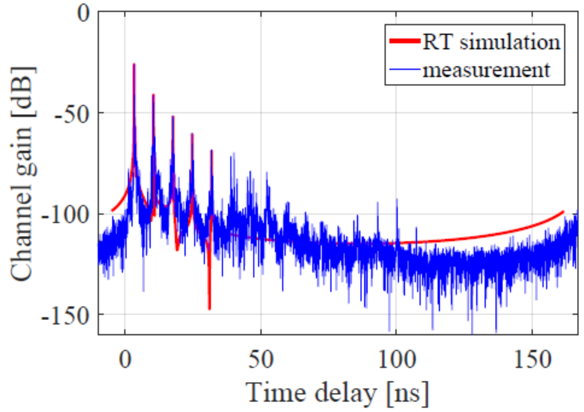
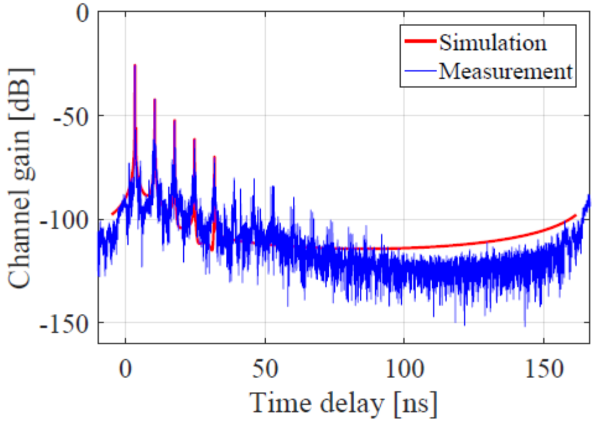
Power delay profile (PDP)



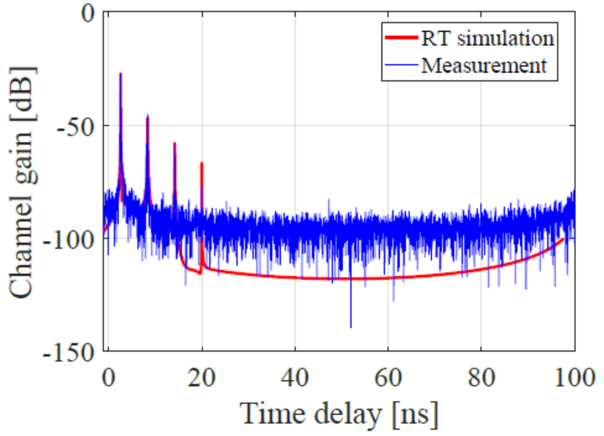
(a) 75-110 GHz



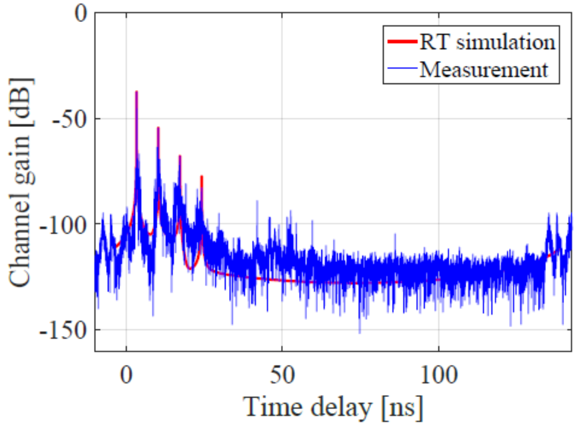
(b) 110-140 GHz



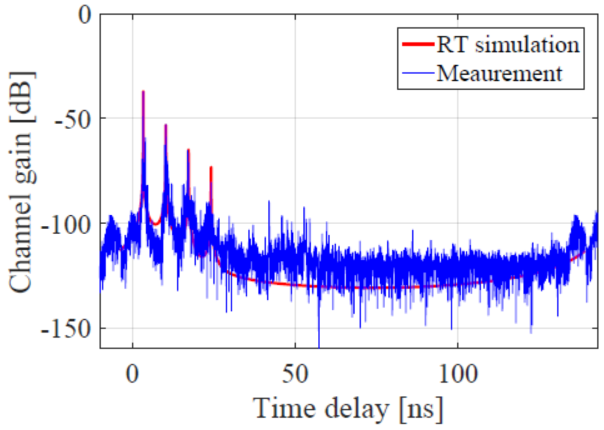
(c) 140-170 GHz



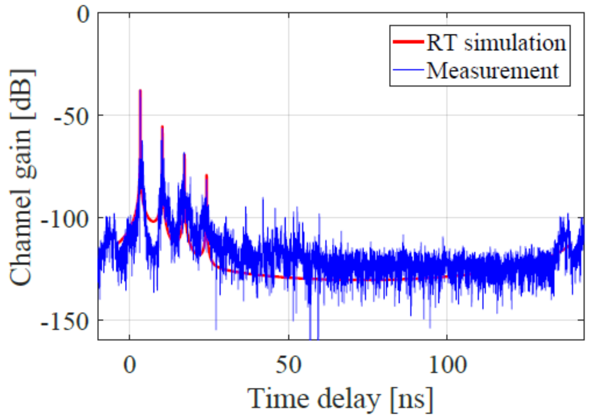
(d) 180-220 GHz



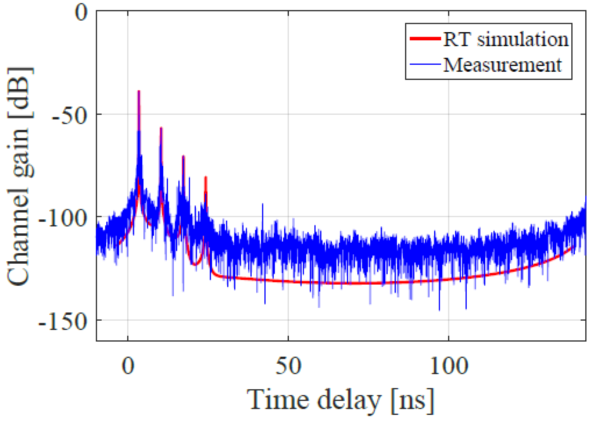
(e) 260-295 GHz



(f) 295-330 GHz

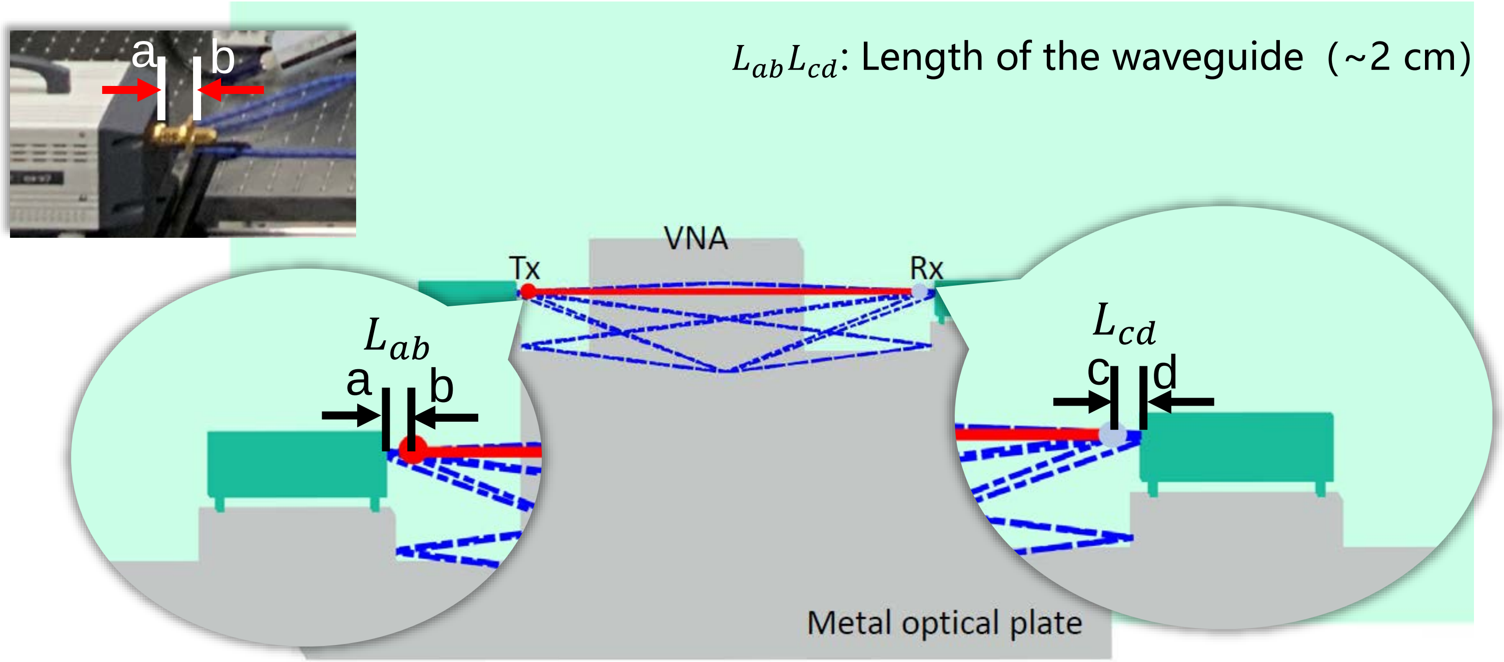


(g) 330-365 GHz

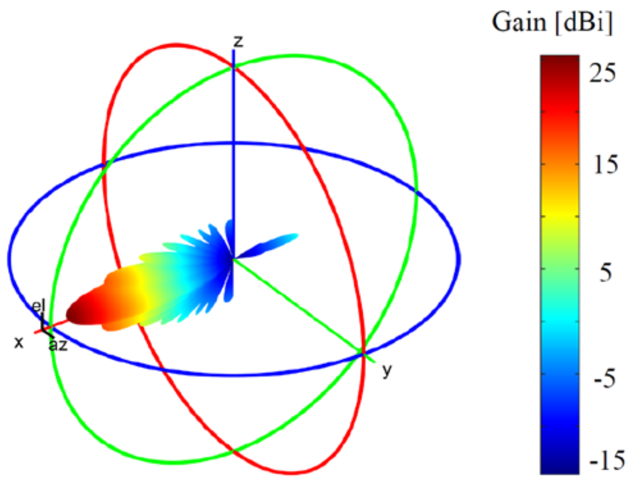


(h) 365-400 GHz

Ray-tracing Simulations



3D antenna pattern



- **RT** can **physically** and **intuitively** explain the **multipaths**
- The power of the **reflected rays** from optical plate and VNA screen is **lower** than the **LOS ray** by more than 40 dB due to the antenna lobe
- The **multi-order reflected paths** are reflected from the frequency extender.

THz Channel Characterization and Analysis

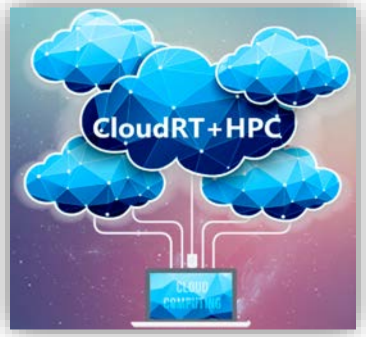
Extracted EM Property of the Painted Metal

Frequency range	75-110 GHz	110-140 GHz	140-170 GHz	180-220 GHz	260-295 GHz	295-330 GHz	330-365 GHz	365-400 GHz
ε'	1.15	1.15	1.15	1.05	1.05	1.4	1.05	1.05
ε''	19.74	19.50	17.50	10.67	12.19	10.71	10.95	10.67

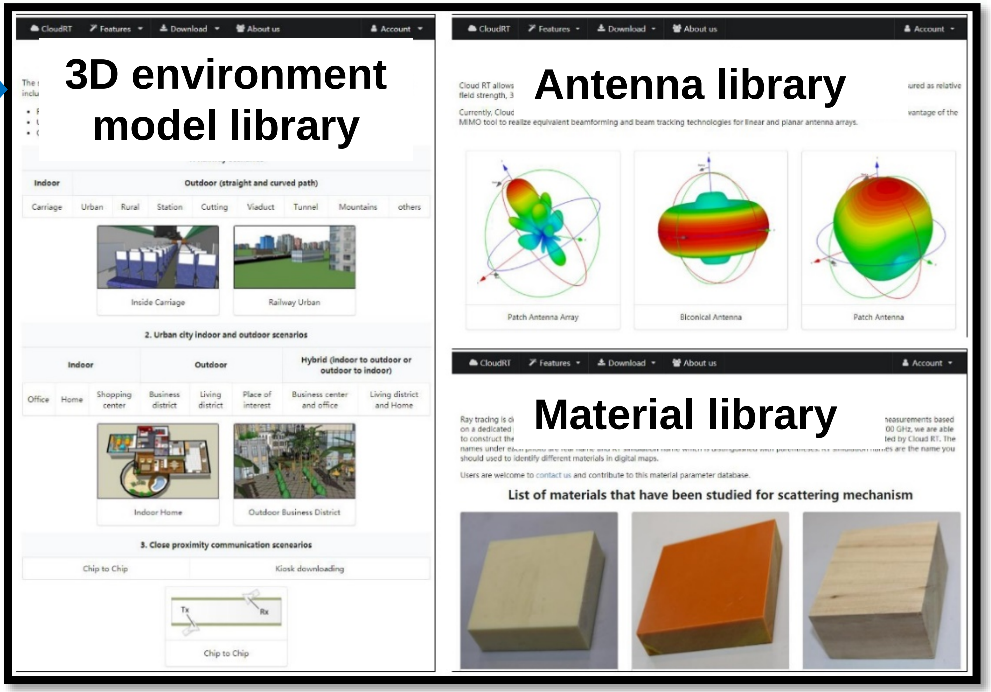
- By the comparison of measured and simulated PDPs, the **power** and **delay** of **multi-order reflected paths match well** with each other.
- **EM properties** can be inversed by RT simulations, as listed in the Table.
- ε'' is considerably small compared to the perfect conductor because of the painting material.
- The **absolute errors** in **power** and in **time delay** of each significant ray are smaller than **1 dB** and **0.1 ns**. The **narrow absolute error** at these measured frequency bands indicates the **EM properties**, the **validated RT engine**, and **the 3D geometry model** can appropriately **repeat the channel sounding measurement results.**

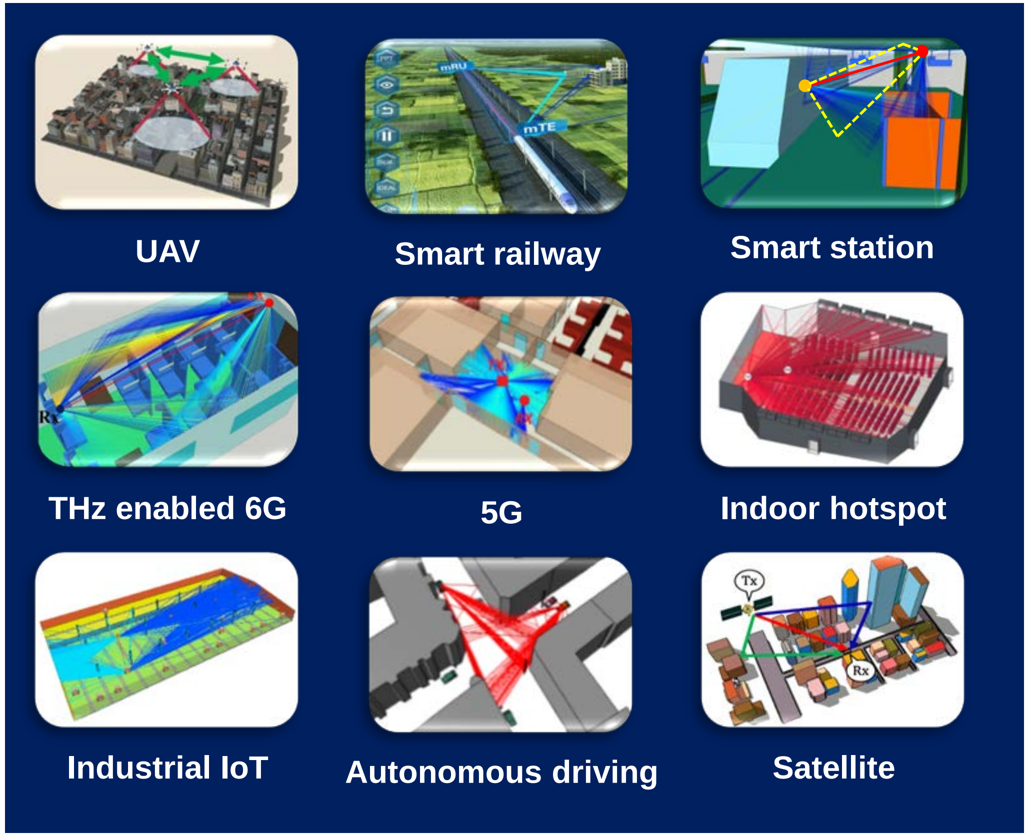
High Performance Ray-tracing Platform

High Performance Ray-tracing Platform CloudRT (http://www.raytracer.cloud)



7000+ users from 60+ countries since June 2018 (online open access)

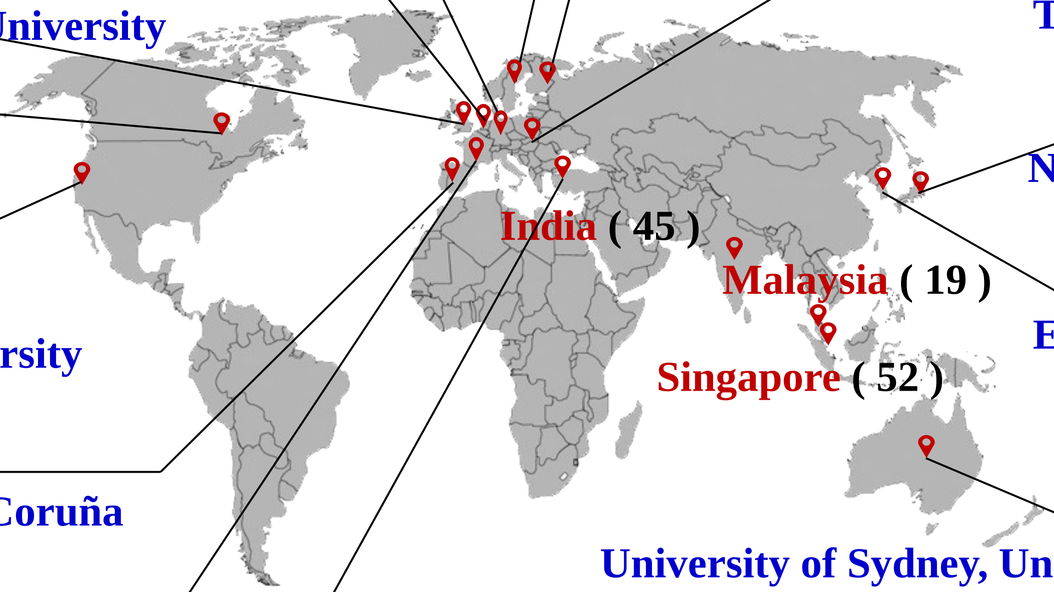




HPC platform: 600 CPU cores, 5 GPUs, and 44 TB storage
Accuracy: validated by 20+ measurements (0.1-300 GHz), with the RMSE < 6 dB

D. He, B. Ai, **K. Guan**, L. Wang, Z. Zhong, and T. Kuerner "The Design and Applications of High-Performance Ray-Tracing Simulation Platform for 5G and Beyond Wireless Communications: A Tutorial," ***IEEE Communications Survey and Tutorial***, vol. 21, no. 1, pp. 10-27, Aug. 2018. **(2021 ESI highly cited paper)**

More than 1900 users from 61 countries



Germany (101 IP)
TU Munich, TU Braunschweig, TU Berlin

Britain (60 IP)
University of Edinburgh

Belgium (35 IP)
KU Leuven， Ghent University

Canada (65 IP)
University of Victoria

The United States (606 IP)
University of Southern California, Cornell University, New York University

Spain (98 IP)
UPM, UPC, UPV, Universidade da Coruña

France (120 IP)
University of Lille, IFSTTAR, Telecom Paris

Turkey (14 IP)
Koc University, Istanbul Technical University

Sweden (43 IP)
Chalmers University of Technology, KTH Royal Institute of Technology

Finland (48 IP)
University of Oulu

Austria (53 IP)
Technische Universität Wien

Japan (95 IP)
Niigata University, Osaka University

South Korea (82 IP)
ETRI, Samsung, Inha University

India (45)

Malaysia (19)

Singapore (52)

Australia (17 IP)
University of Sydney, University of Technology Sydney

Portugal (45): Universidade de Aveiro; Ireland (25): University College Dublin, Dublin City University; Netherlands (16): University of Twente, TU Delft; Russia (19); Iran (18); Pakistan (17); Greece (17); Poland (16); Slovenia (10); Lithuania (9); Indonesia (8); Norway (2); Denmark (2); Albania (2); New Zealand (2); others (…)

More than 5600 users in China

Beijing (2400 IP)
Tsinghua University, Beijing University of Posts and Telecommunications,
Beihang University, China Mobile, China Unicom

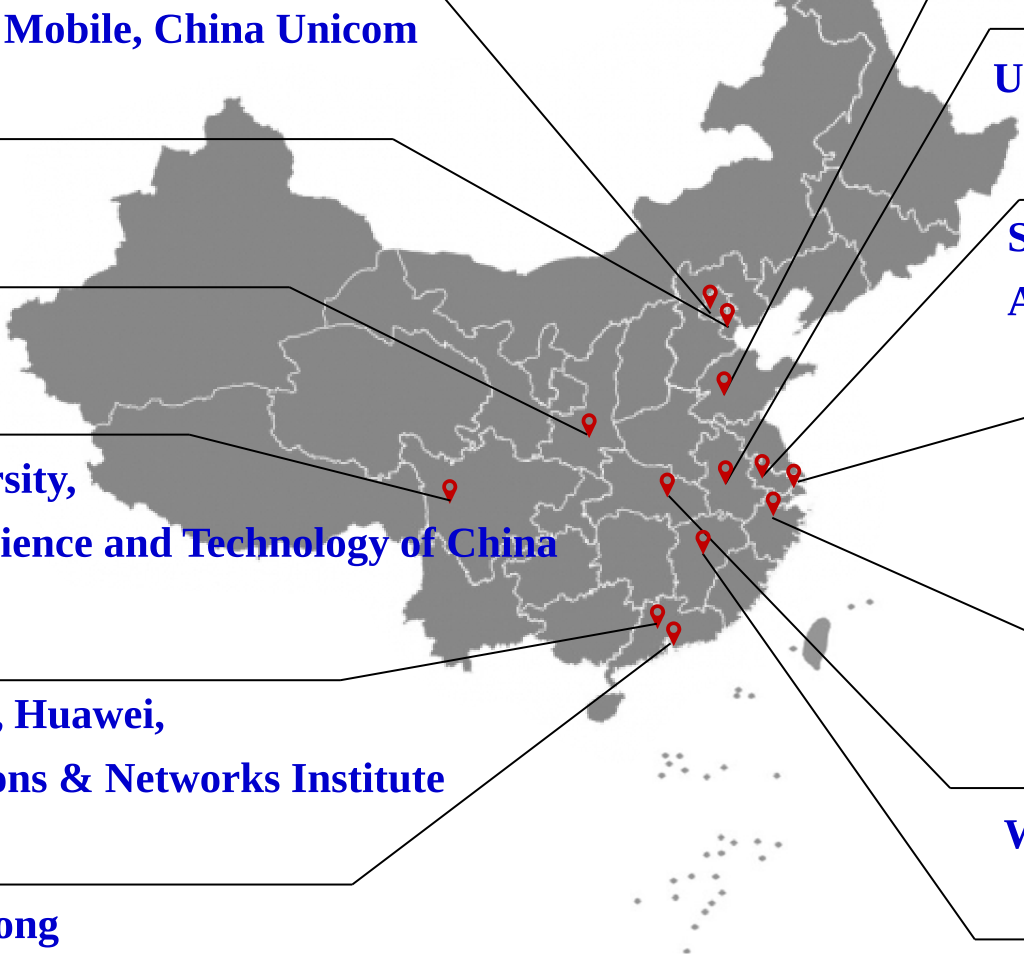
Tianjin (236 IP)
Tianjin University

Shaanxi (53 IP)
Xi’an Jiaotong University

Sichuan (138 IP)
Southwest Jiaotong University,
University of Electronic Science and Technology of China

Guangdong (394 IP)
Shenzhen University, ZTE, Huawei,
Guangdong Communications & Networks Institute

Hong Kong (17 IP)
City University of Hong Kong



Shandong (260 IP)
Shandong University

An Hui (183 IP)
University of Science and Technology of China

Jiangsu (237 IP)
Southeast University, Nanjing University of
Aeronautics and Astronautics

Shanghai (260 IP)
Shanghai Jiaotong University,
Shanghai University

Zhejiang (180 IP)
Zhejiang University

Hubei (137 IP)
Wuhan University of Science and Technology

Jiangxi (52 IP)
Nanchang University, Jiangxi Mobile

Other provinces (883 IP)

THz Channel Characterization and Analysis

Root-Mean-Square (RMS) delay spread

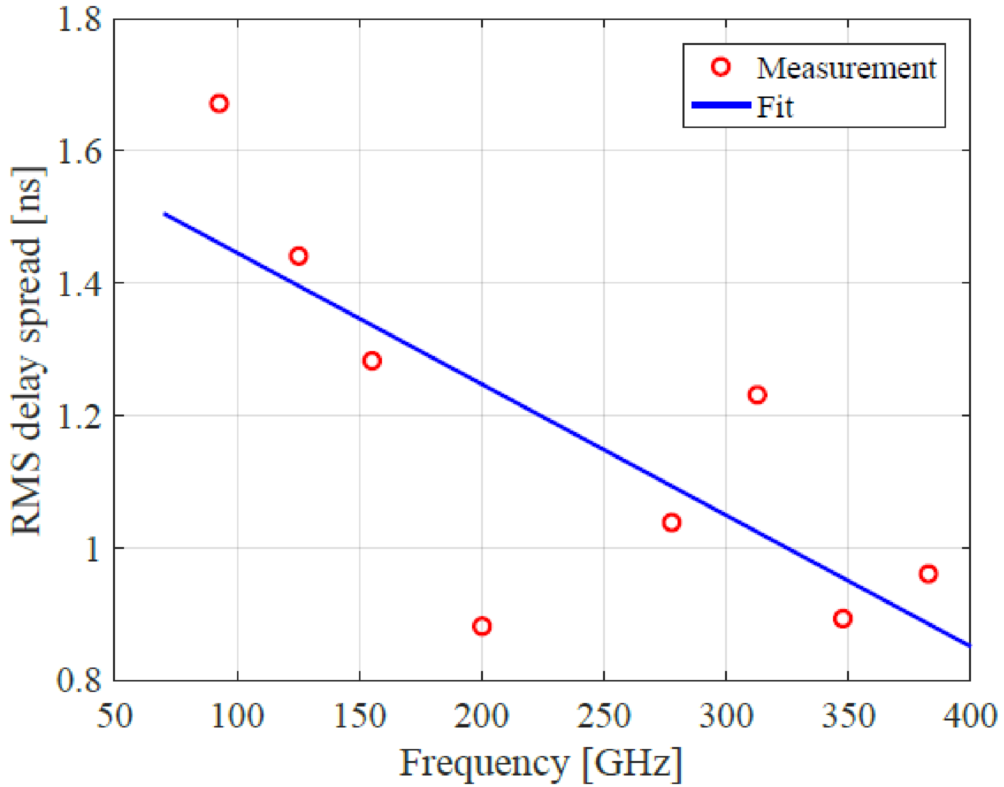
$$\sigma_\tau = \sqrt{\frac{\sum_{n=1}^{N} {\tau_n}^2 \cdot P_n}{\sum_{n=1}^{N} P_n} - \left(\frac{\sum_{n=1}^{N} \tau_n \cdot P_n}{\sum_{n=1}^{N} P_n} \right)^2}$$

in which P_n and τ_n are the power and the time delay of the *n*th multipath, respectively.

The figure shows the performance of RMS delay spread with frequency. A linear function is used to model the relationship:

$$DS = -0.0020 f + 1.6443$$

- **As the frequency increases, the propagation loss of each multipath increases, resulting in a smaller RMS delay spread.**



absolute error = 0.134 ns
standard division =0.184 ns

THz Channel Characterization and Analysis

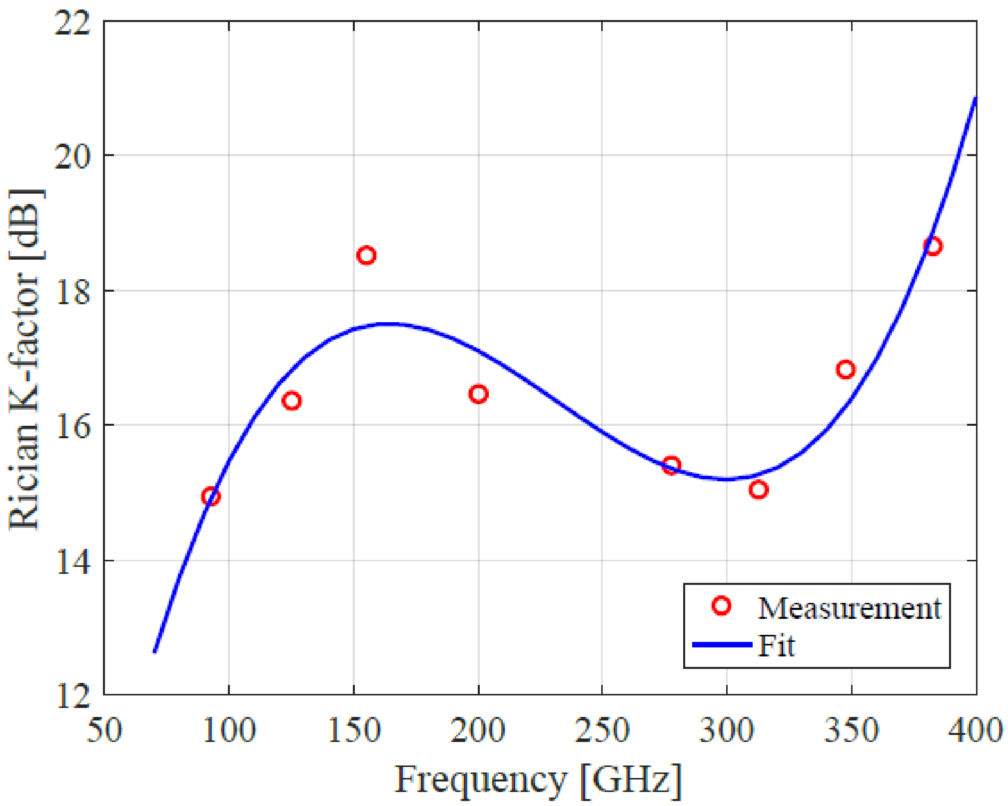
Rician K-factor

$$KF = \frac{P_d}{\sum P(i) - P_d}$$

where $P(i)$ is the energy of all the paths of the signal during propagation, P_d is the energy of the LOS path.

The figure shows the performance of Rician K-factor with frequency. A cubic function is used to model the relationship:

$$KF = 1.86 \times 10^{-6} f^3 - 0.0013 f^2 + 0.2737 f - 0.8565$$



absolute error = 0.401 dB
standard division =0.548 dB

- **Rician K-factors are high enough to imply a LOS condition.**

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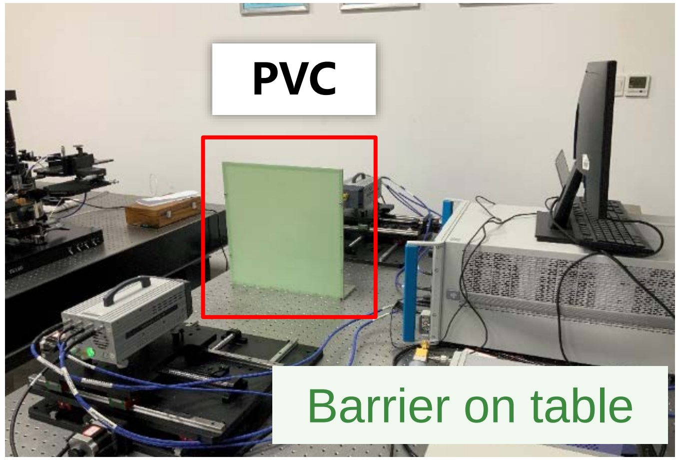
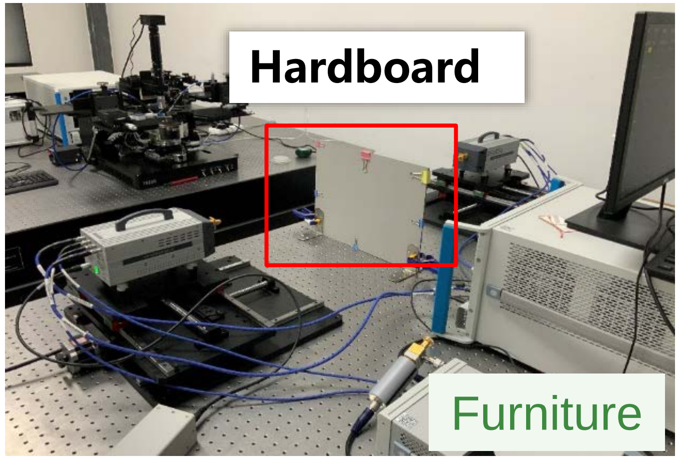
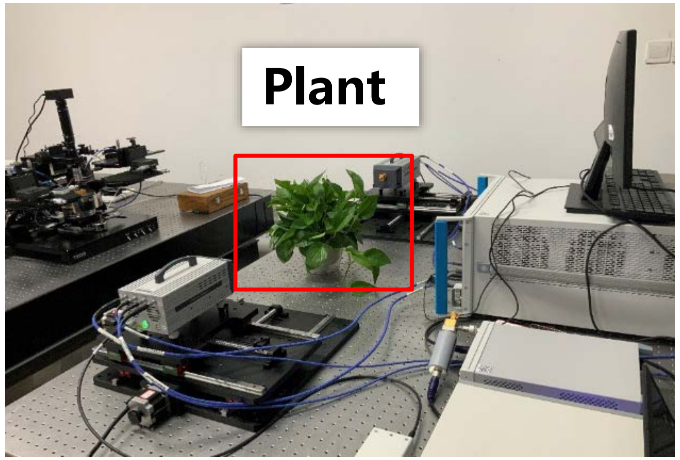
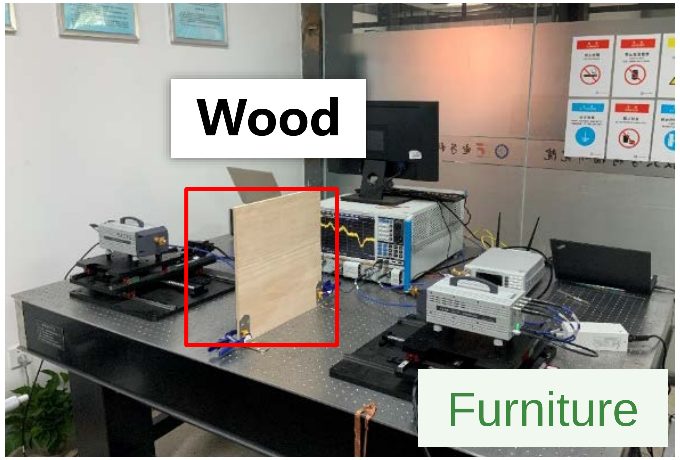
Channel Measurement Campaigns (Penetration Loss)

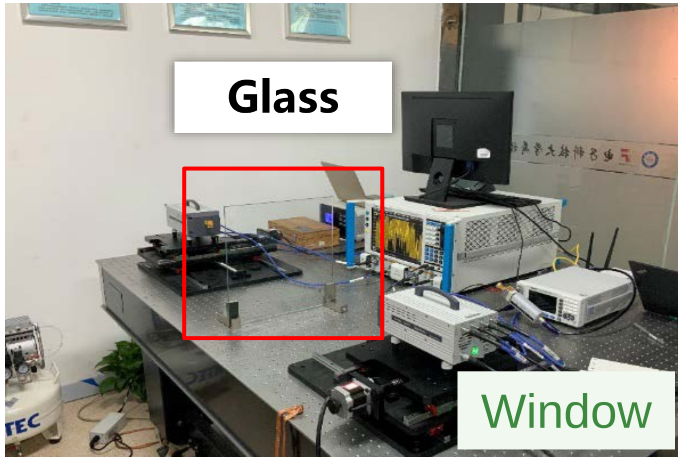
Penetration Measurement for Very Common Materials in Indoor Scenario





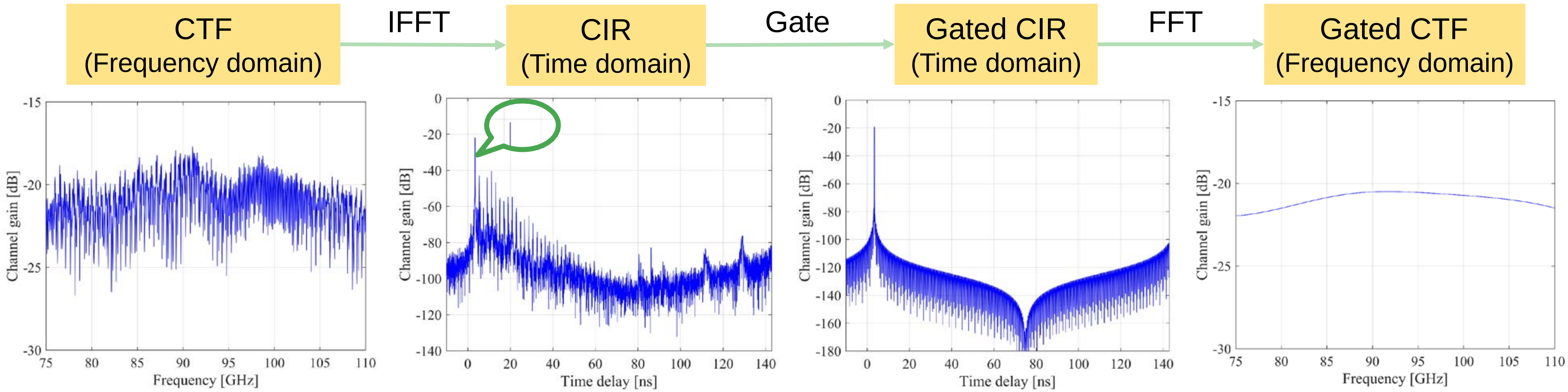






Material	Thickness
PVC	2 mm
Hardboard	6 mm
Wood	10 mm
Glass	6 mm
Plant	-

Numerical Results and Analysis



- VNA： **Frequency**-domain measurement, **S21** parameter recorded
- A **time gate** is added on the LOS path to **isolate unnecessary reflection** from the measurement environment.
- The gated curve is transformed into the frequency domain, which has removed the influence of interferential factors.
- We compare the sample measurements to a reference LOS measurement, which corresponds to the direct path without any obstacles between Tx and Rx

$$Penetration(f) = P_{LOS}(f) - P_{NLOS}(f) \quad [\mathrm{dB}]$$

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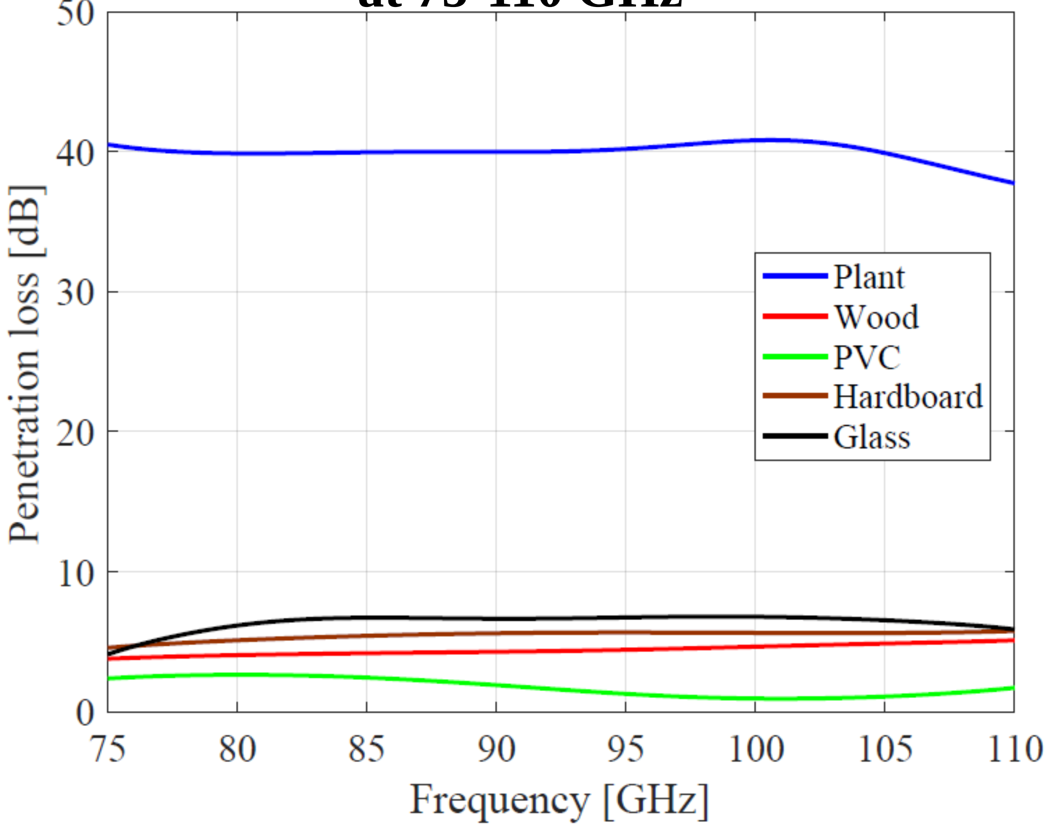
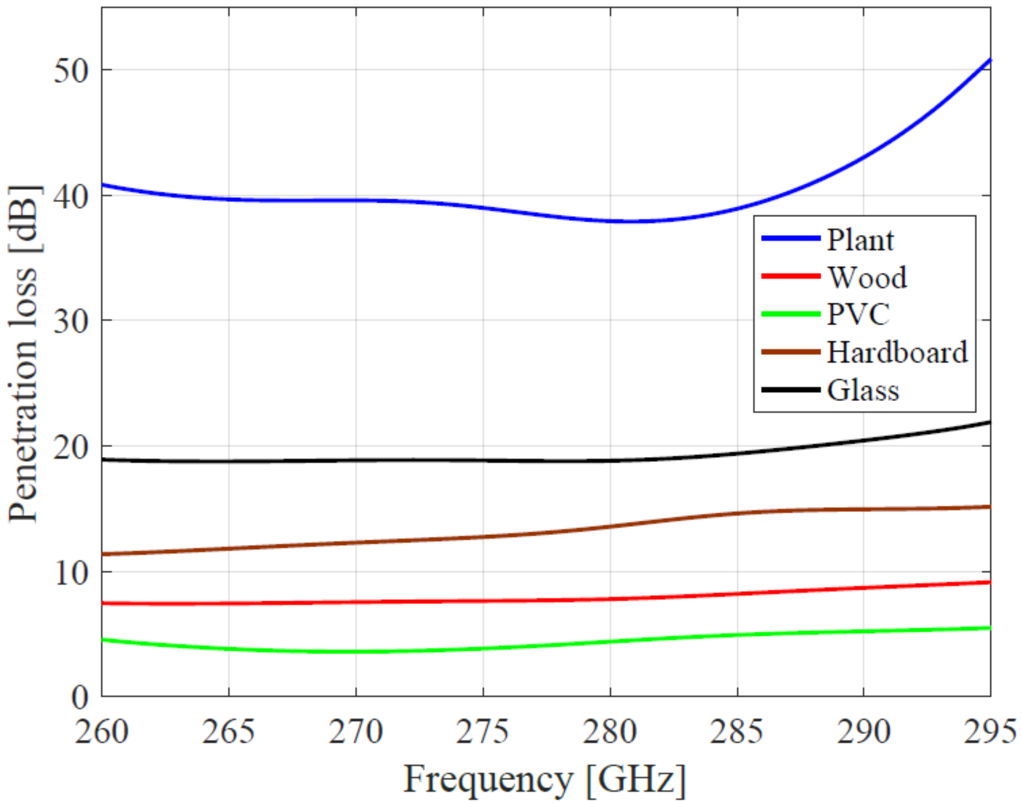
Numerical Results and Analysis

at 75-110 GHz



at 260-295 GHz



Loss [dB]	Glass	Hardboard	Wood	PVC	Plant
75-110 GHz	6.41	5.47	4.41	1.76	39.98
260-295 GHz	19.32	13.30	7.96	4.37	40.41

Numerical Results and Analysis

Loss [dB]	Glass	Hardboard	Wood	PVC	Plant
75-110 GHz	6.41	5.47	4.41	1.76	39.98
260-295 GHz	19.32	13.30	7.96	4.37	40.41

- The penetration loss is **increased with frequency** for all tested samples.
- The **potted plant**, which is a very common decoration on the table in the office or in the living room, causes **a very large penetration loss**. One of the reasons is that the water molecules inside the plant make the energy of waves absorbed.
- Electromagnetic waves can indeed **transmit some materials**, such as wood and plastic, with relative little penetration loss.
- **Idea**: glass window may be replaced by hard transparent plastic. **Better outdoor-to-indoor coverage** may be achieved.

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  - Numerical Results and Analysis
- **Conclusion and Future Work**

Conclusion

- We introduce extensive channel measurements from 75 GHz to 400 GHz on a desktop.
- A self-developed RT simulator is utilized to post-process and to locate the received multipaths.
- With the help of RT simulations, the EM properties of the painted metal are extracted. The painted metal is the relevant material generating multi-order reflected paths in the measurements.
- In addition, the RMS delay spread and Rician K-factor are extracted and analyzed. A linear function and a cubic function are utilized to model these two channel parameters with frequency, respectively.
- In order to describe the channel characteristics in the presence of obstruction, we measure the penetration loss for several common materials (glass, hardboard, wood, plastic, and potted plant). As expected, the penetration loss increases with the increase of frequency for all tested samples.

Future Work

- We will conduct more channel measurements with narrower frequency band in the same desktop scenario. Thus, the KF and RMS delay spread can be extracted to validate the corresponding fitted curves at THz band.
- We will conduct more penetration measurements for these materials with different thickness. Thus, the changes of the penetration loss will be discussed with the changes of the thickness.

Thank Your for Your Attention

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