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

Submission Title: Towards 6G: Paradigm of Realistic Terahertz Channel Modeling

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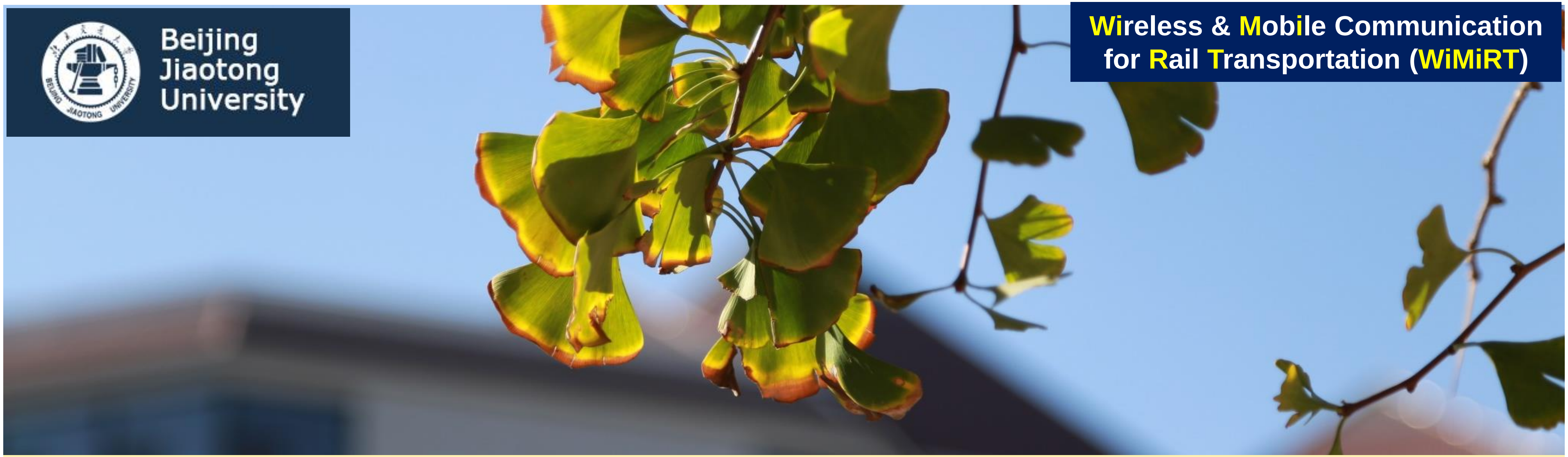
Re: n/a

Abstract: In order to break through the bottleneck of scarce full-dimensional channel sounding measurements, this document presents a novel paradigm for terahertz (THz) channel modeling towards 6G. With the core of high-performance ray tracing (RT), the presented paradigm requires merely quite limited channel sounding to calibrate the geometry and material electromagnetic (EM) properties of the three-dimensional (3D) environment model in the target scenarios. Then, through extensive RT simulations, the parameters extracted from RT simulations can be fed into either ray-based novel stochastic channel models or cluster-based standard channel model families. Verified by RT simulations, these models can generate realistic channels that are valuable for the design and evaluation of THz systems.

Purpose: Information of IEEE 802.15 SC THz

Beijing Jiaotong University

Wireless & Mobile Communication for Rail Transportation (WiMiRT)



Towards 6G: Paradigm of Realistic Terahertz Channel Modeling

Ke Guan[1,2], Haofan Yi[1,2], Danping He[1,2], Bo Ai[1,2], Zhengrong Lai[3], Jianwu Dou[4,5], Pengxiang Li[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] Guangdong Communications & Networks Institute, [4] State Key Laboratory of Mobile Network and Mobile Multimedia Technology, [5] ZTE Corporation, [6] China Telecom Research Institute

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Outline

- Challenges on THz Channel Modeling
- New Paradigm of Realistic Terahertz Channel Modeling
- Three Use Cases from microscopy to macroscopy
  - Close-Proximity Communications
  - THz Communications on a desktop
  - THz Channels for Smart Rail Mobility
- Conclusion

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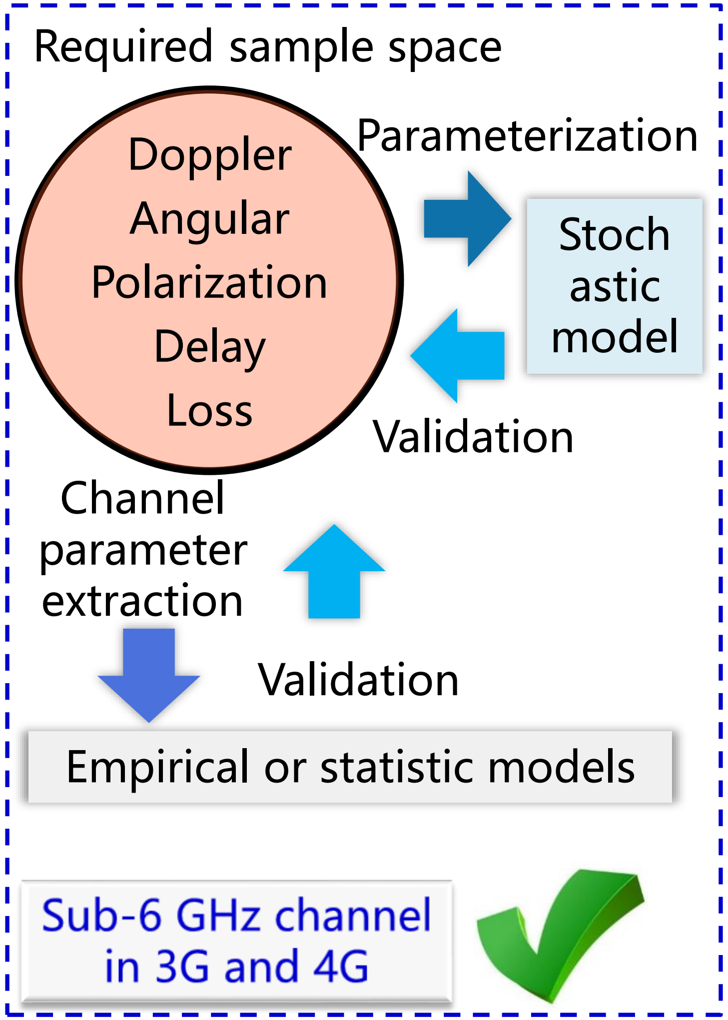
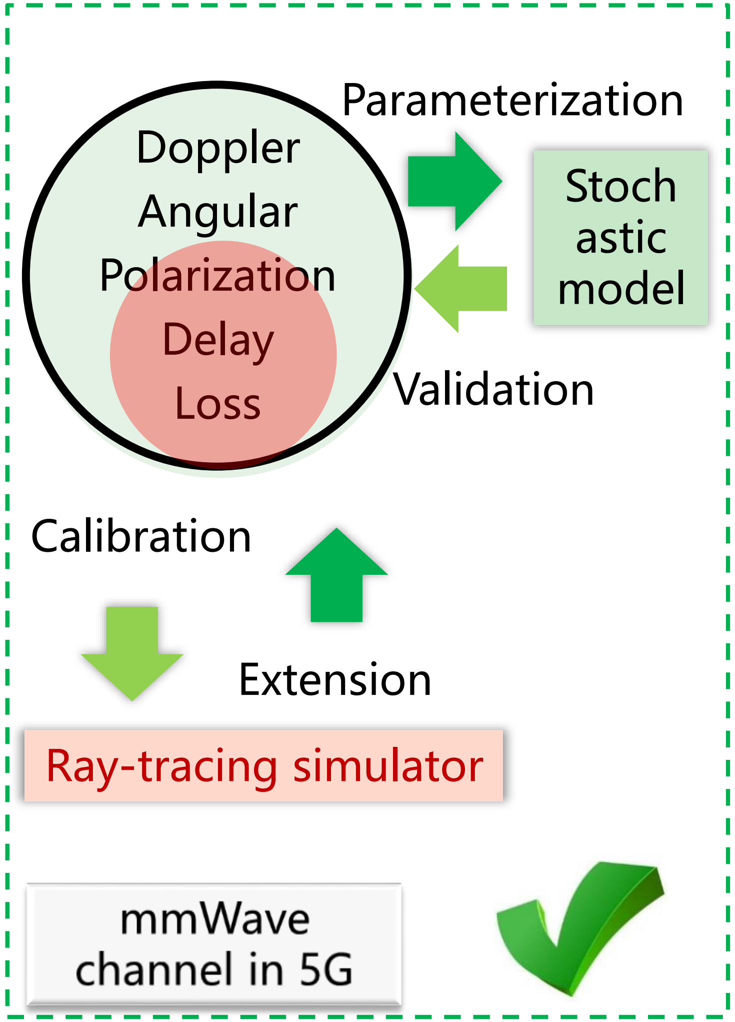
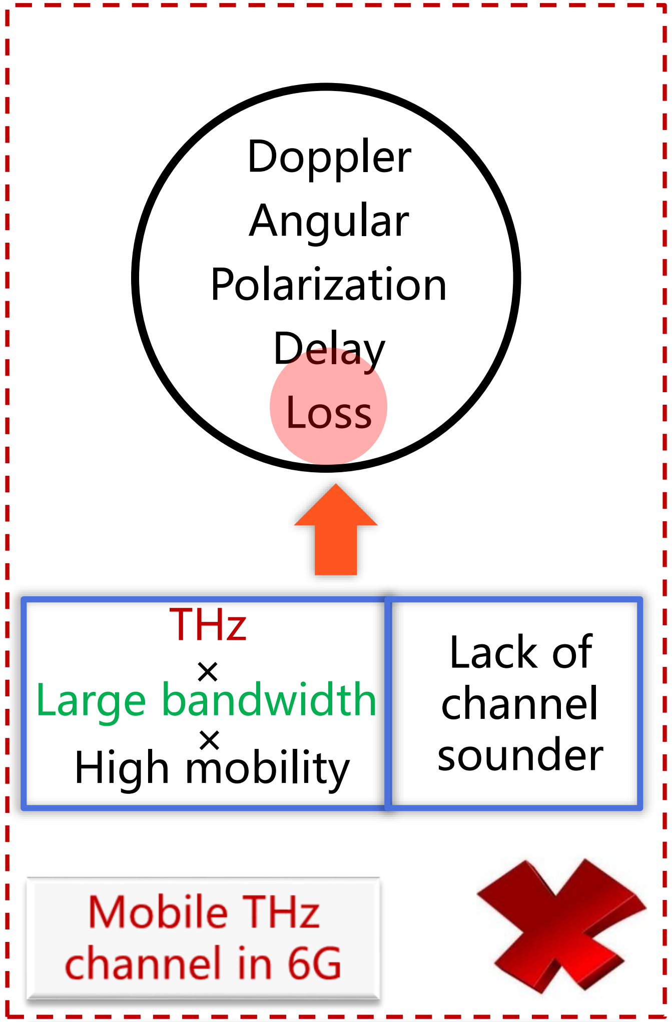
Challenges on Channel Modeling







New paradigm is needed!

Outline

- Challenges on THz Channel Modeling
- **New Paradigm of Realistic Terahertz Channel Modeling**
- Three Use Cases from microscopy to macroscopy
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  - THz Communications on a desktop
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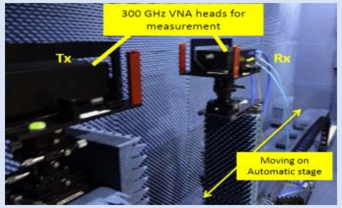
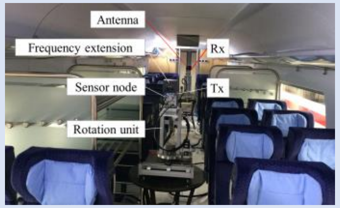
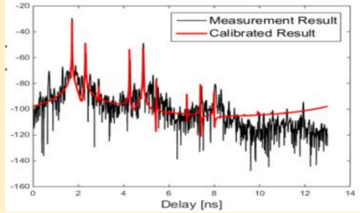
New Paradigm of Realistic Terahertz Channel Modeling

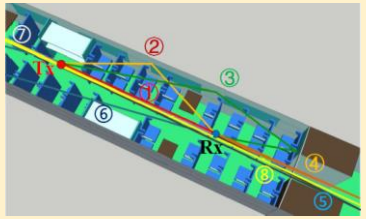


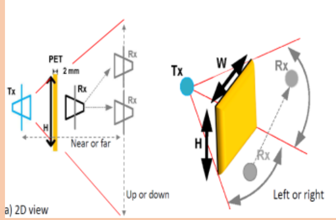
Limited channel sounding



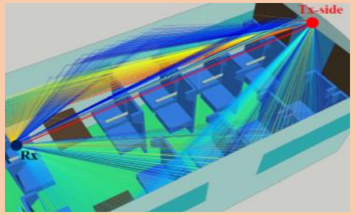


Calibration of RT simulator

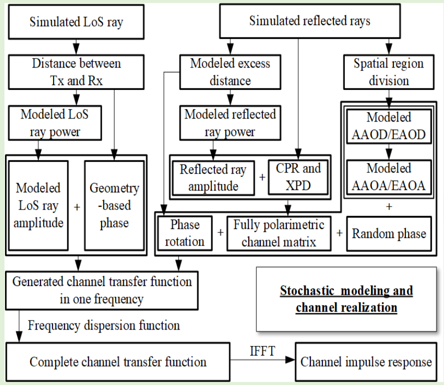




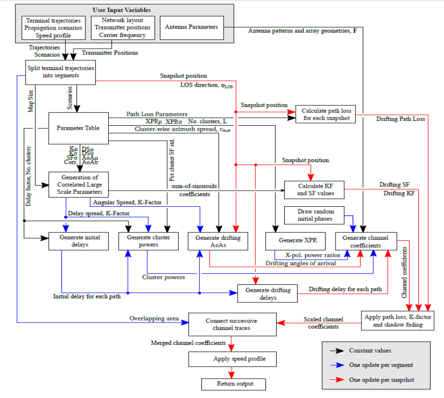
Extensive RT simulations

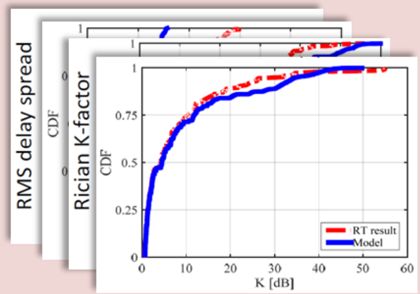


Ray-based novel stocha-stic channel model

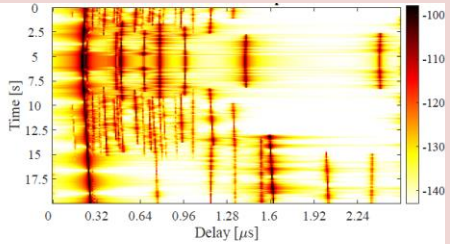


Cluster-based standard channel model families





Realistic THz channel realization

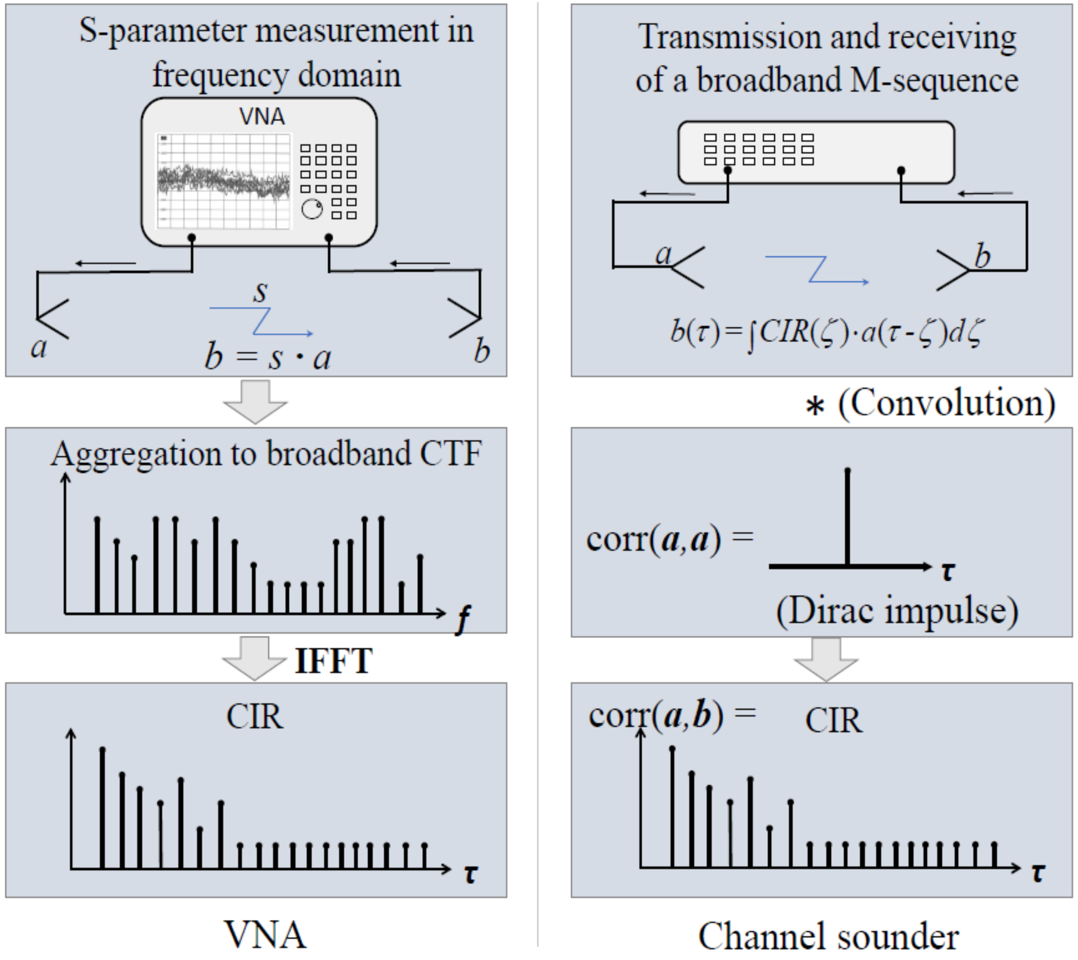


K. Guan, H. Yi, D. He, B. Ai and Z. Zhong, "Towards 6G: Paradigm of realistic terahertz channel modeling," in *China Communications*, vol. 18, no. 5, pp. 1-18, May 2021. (Invited paper)

Paradigm of Realistic Terahertz Channel Modeling

A. Limited channel sounding

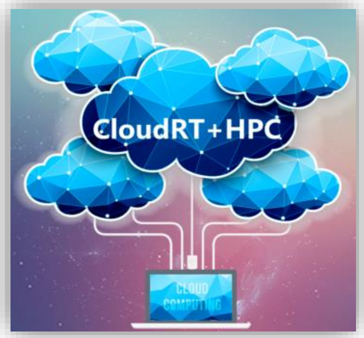
- **VNA-based measurement**
  - In frequency domain
  - CIR ->by IFFT from CTF
  - Pros: accurate broadband system;
    large dynamic range.
  - Cons: long time-consuming;
    cannot capture the dynamic
    channel variations.
- **Channel sounder methodology**
  - In time domain
  - CIR-> Correlation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



Paradigm of Realistic Terahertz Channel Modeling

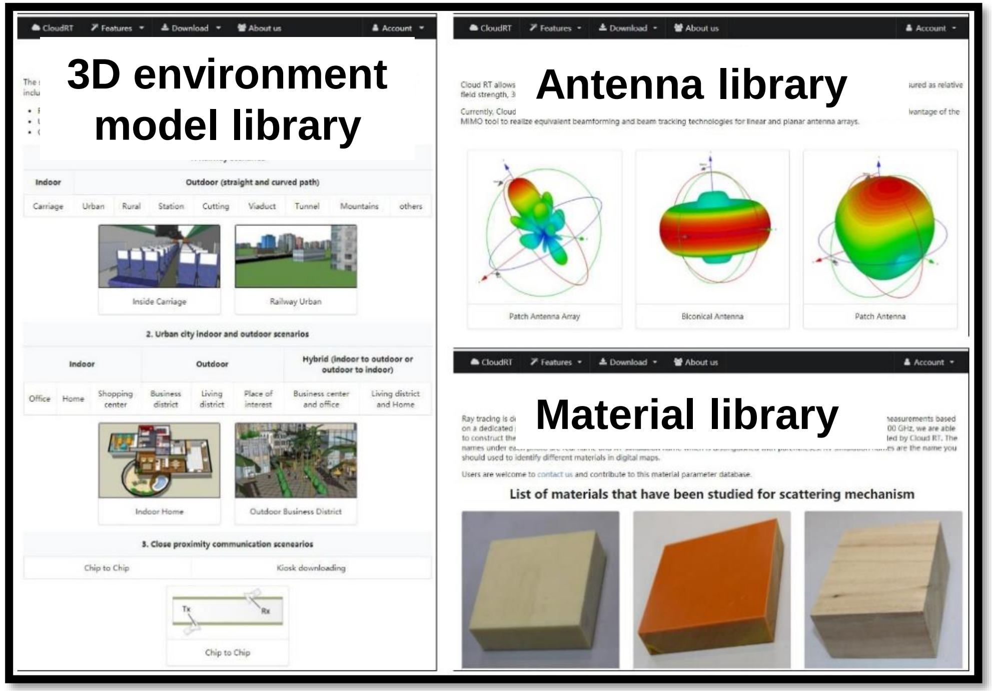
B. Calibration of RT simulator

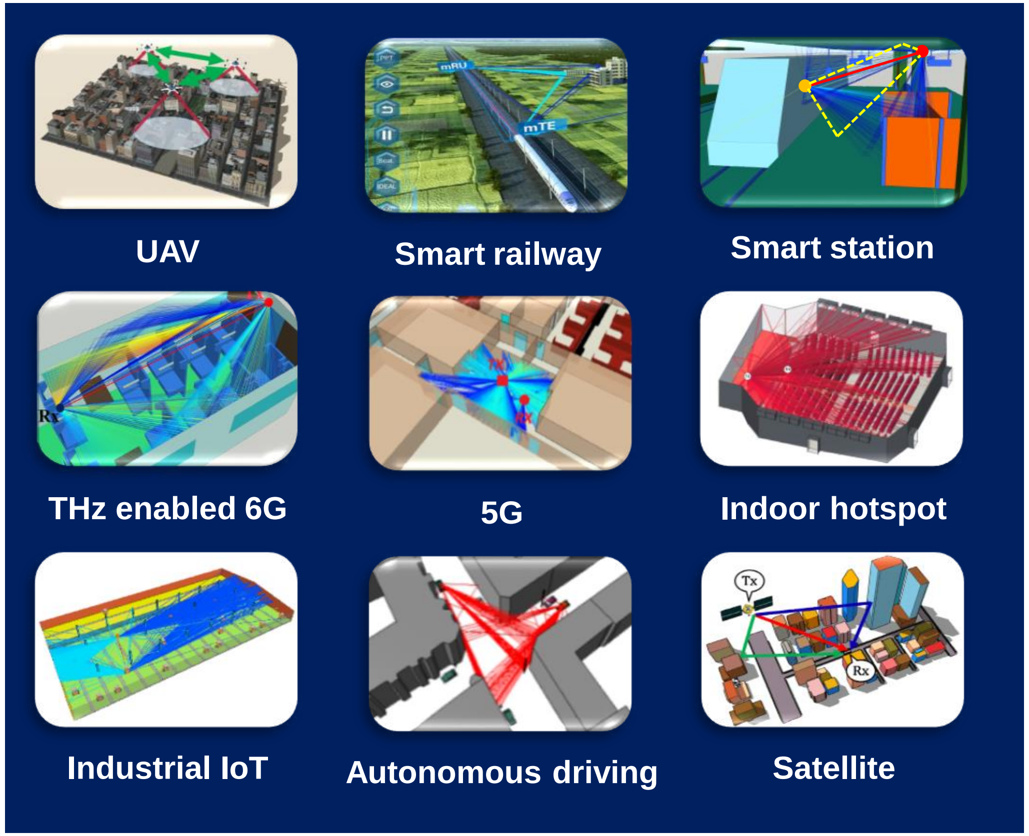
High Performance Ray-tracing Platform CloudRT (http://www.raytracer.cloud)



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

4000+ users from 60 countries since June 2018 (online open access)





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. **(ESI highly cited paper)**

More than 5000 users in China

Beijing (1598 IP)
Tsinghua, China Mobile, China Unicom

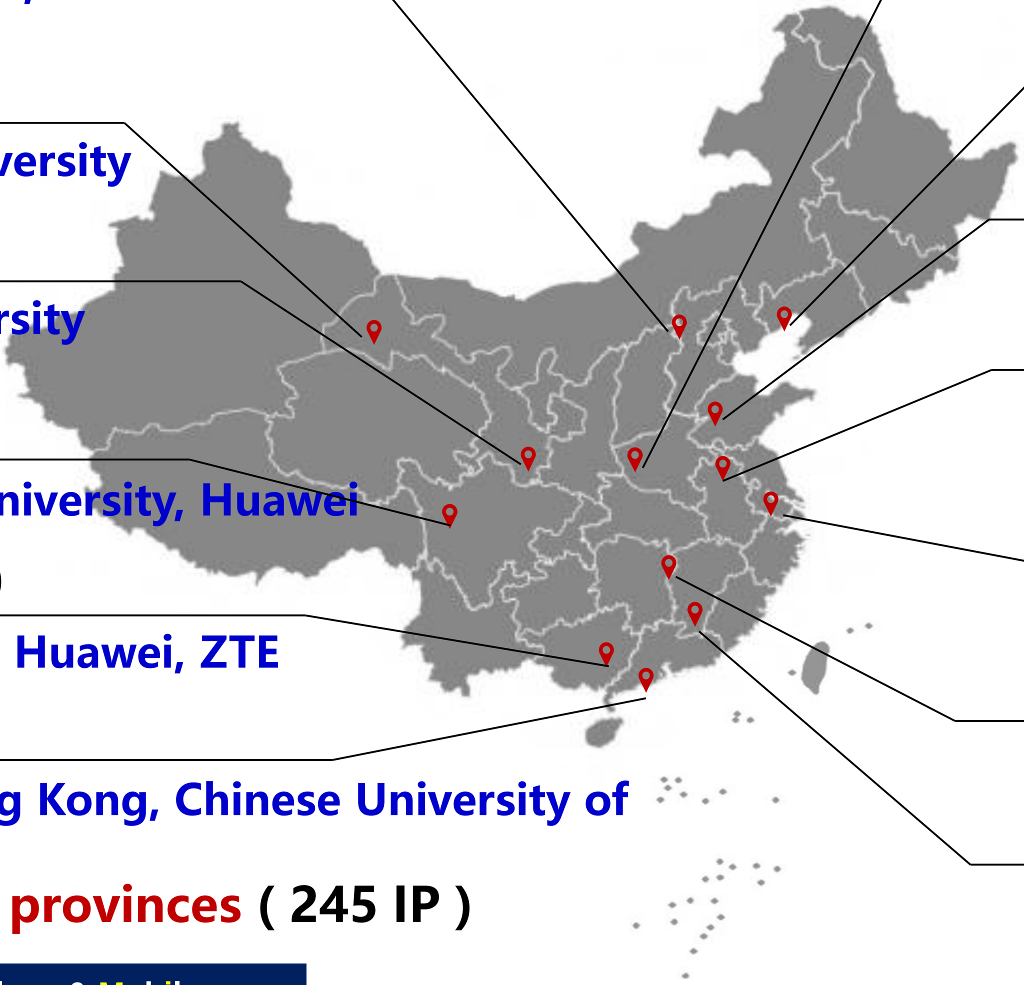
Gansu (8 IP)
Lanzhou Jiaotong University

Shanxi (19 IP)
Xi' an Jiaotong University

Sichuan (60 IP)
Southwest Jiaotong University, Huawei

Guangdong (81 IP)
Zhongshan University, Huawei, ZTE

Hong Kong (5 IP)
City University of Hong Kong, Chinese University of Hong Kong



Zhengzhou University

Liaoning (17 IP)
Dalian University of Technology

Shandong (43 IP)
Shandong University

Jiangsu (61 IP)
Southeast University

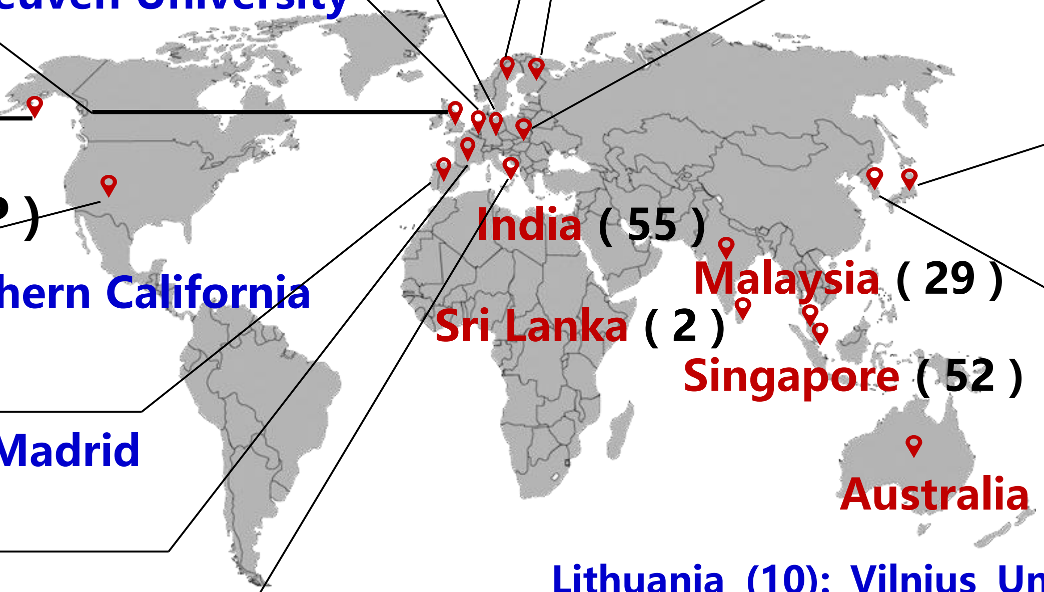
Shanghai (204 IP)
Shanghai Jiaotong University

Jiangxi (31 IP)
Jiangxi Mobile

Fujian (44 IP)
Xiamen University

Other provinces (245 IP)

More than 1900 users from 74 countries



Germany (115 IP)
TU Muenchen、HHI、DLR

England (52 IP)
Cambridge University

Belgium (38 IP)
Leuven University

Canada (73 IP)
University of Toronto

the United States (528 IP)
Stanford, University of Southern California

Spain (119 IP)
The Technical University of Madrid

France (112 IP)
Lille University、IFSTTAR

Italy (9 IP)
University of Bologna, Milan Institute of Technology

Sweden (37 IP)
Chalmers University of Technology

Finland (167 IP)
Oulu University

Austria (74 IP)
Graz university of technology

Japan (154 IP)
Niigata university

South Korea (39 IP)
ETRI

India (55)

Malaysia (29)

Sri Lanka (2)

Singapore (52)

Australia (21)

Lithuania (10): Vilnius University; Slovenia (10): Joseph Stefan Institute; Denmark (3): University of orburg; Ireland (10): Dublin City University; Portugal (57); Netherlands (7): Delft technology; Norway (7); Pakistan (4); Albania (2); new Zealand (1); Poland (16; Vietnam (4); Iran (16); Indonesia (2); others (...)

Paradigm of Realistic Terahertz Channel Modeling

C. Extensive RT simulations

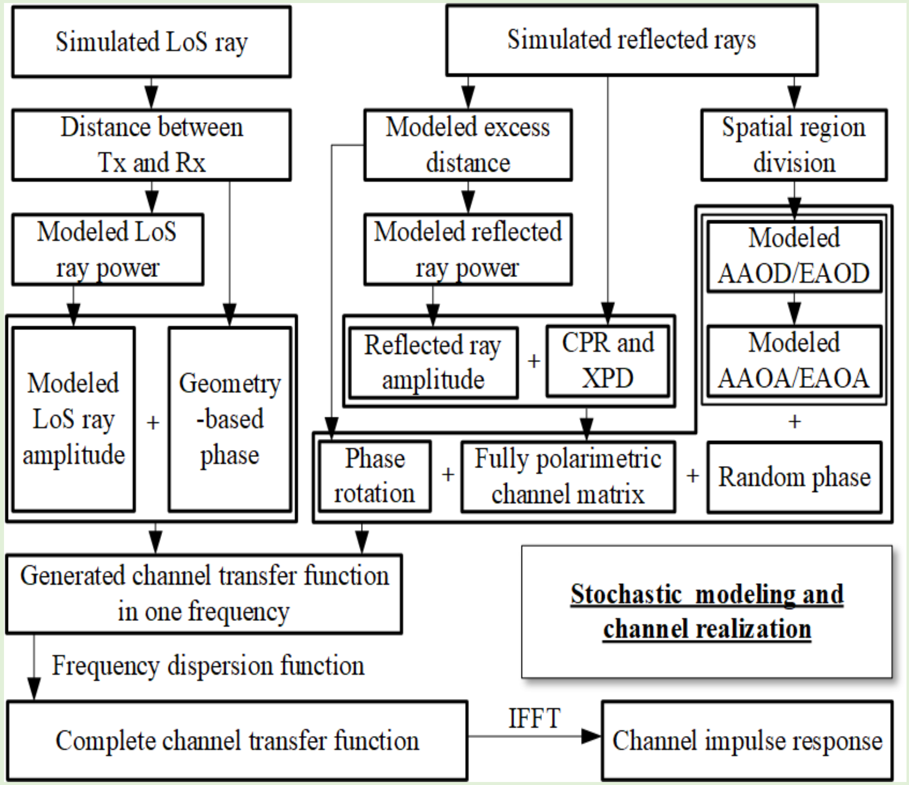
2D channel measurement ➡ 3D channel simulations

- **Various positions** of **Tx** and **Rx**;
- **Full polarization** combinations (VV, VH, HV, HH);
- **Various pattern coupling**, including single antenna, MIMO;
- **Various environments** with similar types of objects and materials, but not necessary with the same geometry or topology;
- **Various mobility patterns** not only for Tx/Rx but also for mobile scatterers, such as vehicles, aircrafts, pedestrians

Paradigm of Realistic Terahertz Channel Modeling

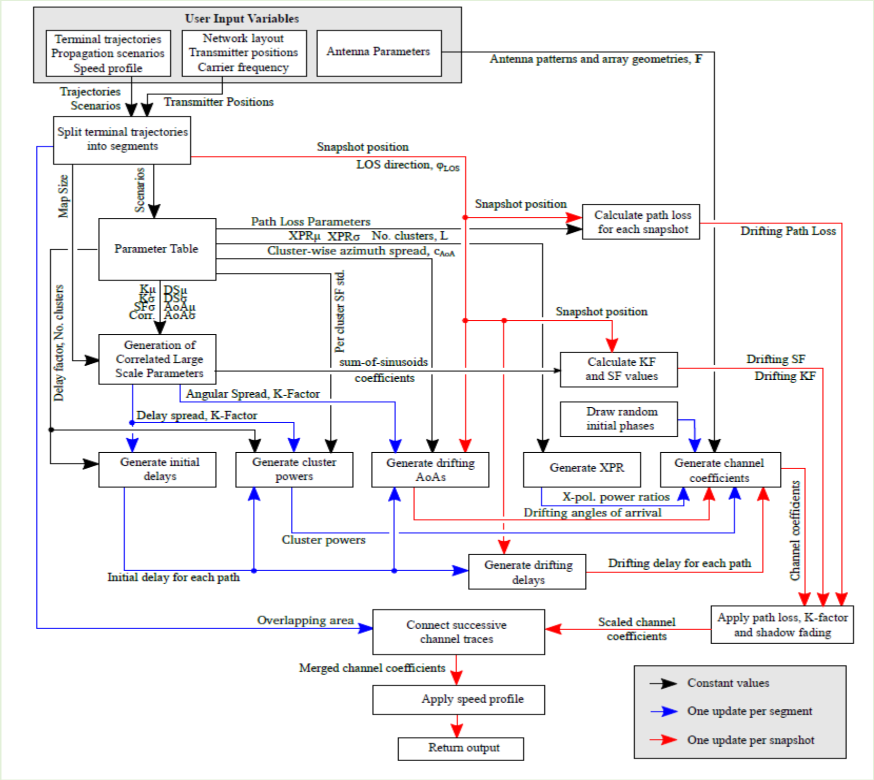
D.

Ray-based novel stochastic channel model



OR

Cluster-based standard channel model families



E. Realistic THz channel realization

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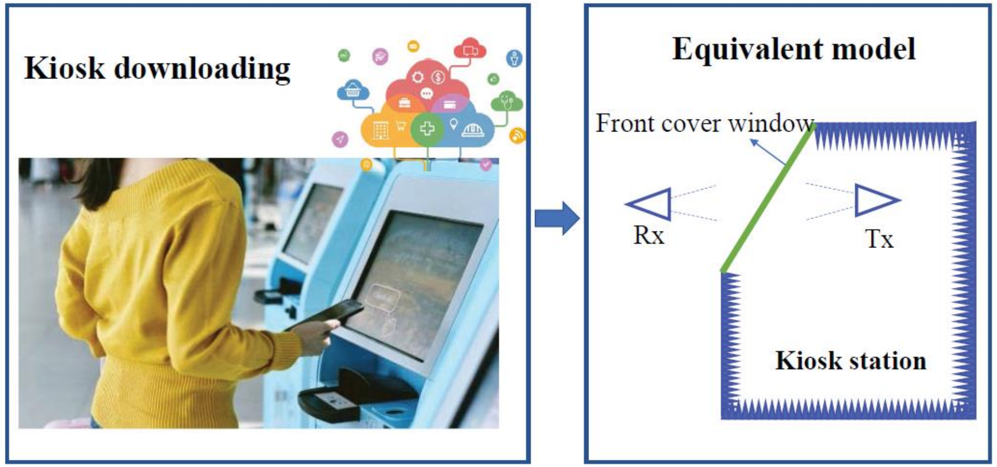
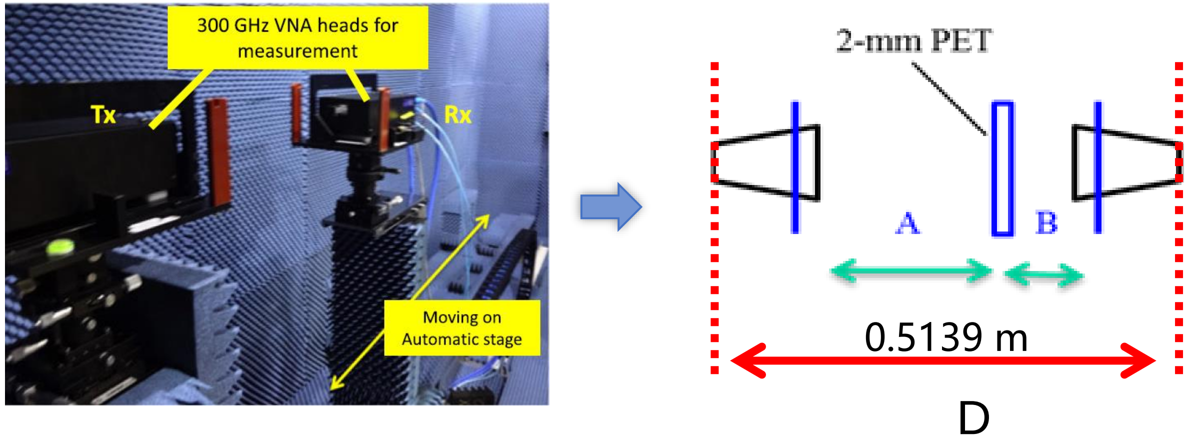
Case Study 1: Close Proximity Communications – Kiosk Downloading

A. Limited channel sounding

Defined kiosk downloading scenario



Measurement campaign



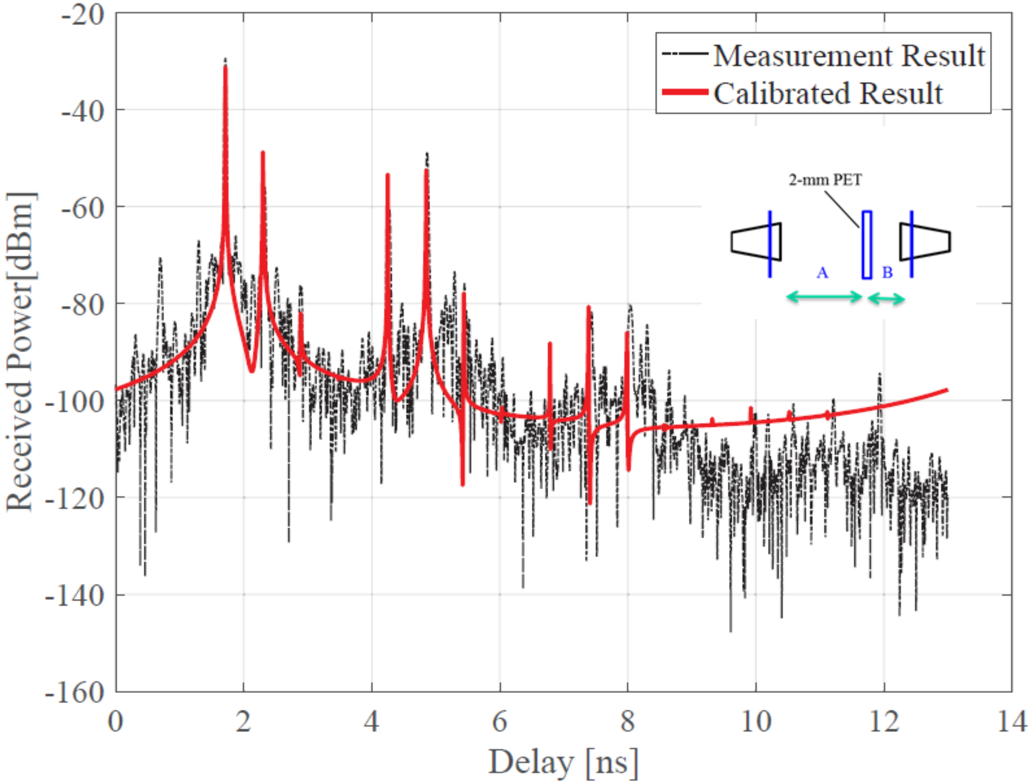
configuration	value
Frequency	220-340 GHz
Bandwidth	120 GHz
IF bandwidth	5 kHz

Antenna related	value
Gain	25 dBi
HPBW	10°
Distance (Tx->Rx)	0.5139 m

Case Study 1: Close Proximity Communications – Kiosk Downloading

B. Calibration of RT simulator

CIR - After Calibration:



EM Properties Before Calibration:

Material	ε_r	$\tan\delta$
Metal	1.0	1.0E7
PET	6.4	0.1172

EM Properties After Calibration:

Material	ε_r	$\tan\delta$
Metal	1.0	1.0E7
PET	6.4	0.1172

Transmitted loss by PET: A_PET=1.9890 dB

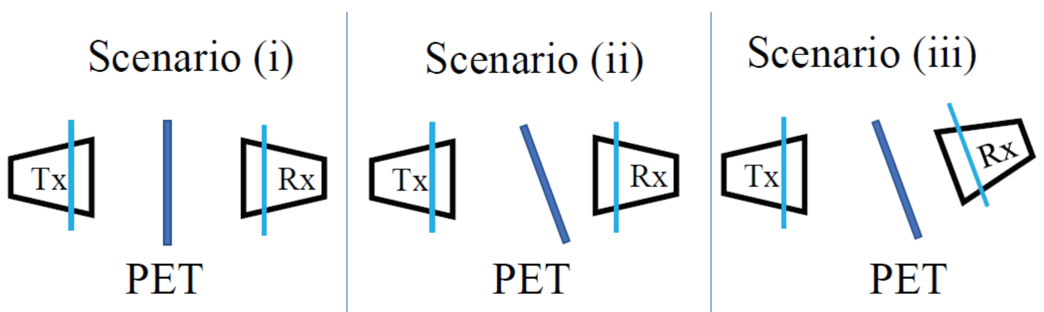
- **Mean abs. error=0.1027 dB**

Case Study 1: Close Proximity Communications – Kiosk Downloading

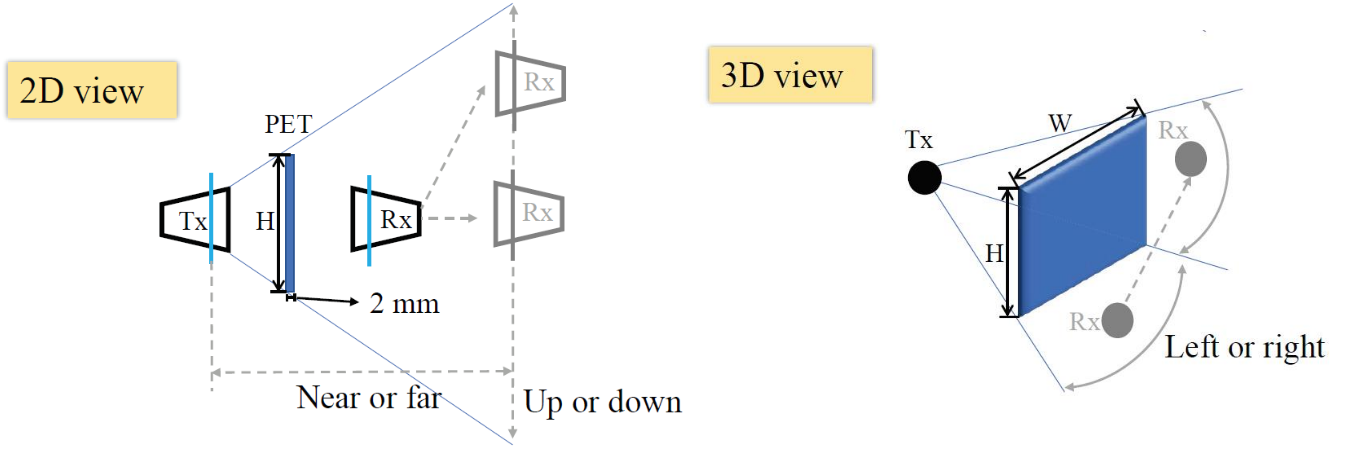
C. Extensive RT simulations

Target Scenario Generation:

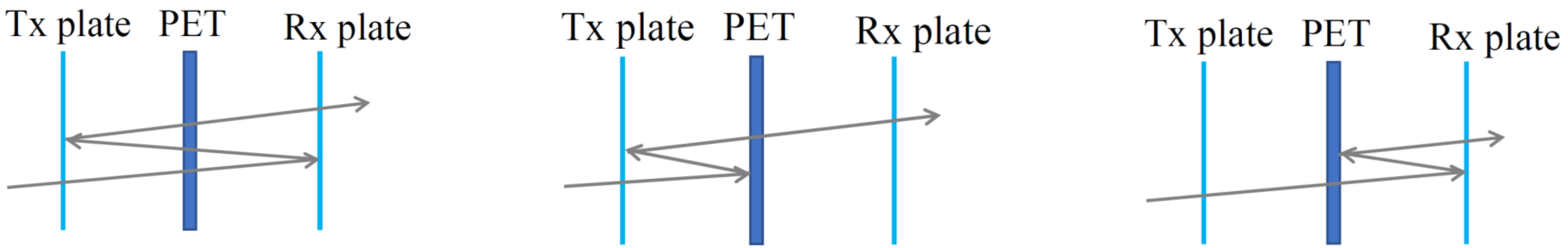
The possible three kiosk downloading scenarios



The 2D and 3D view of Rx position in the extensive RT simulations



Three types of the reflected rays.



Case Study 1: Close Proximity Communications – Kiosk Downloading

D. Ray-based novel stochastic channel model

- Considering only up to 2nd order reflections, due to the high attenuation at higher orders
- 1 transmitted path and 3 second-order reflection paths should be generated

Parameter Extraction-Amplitude of Path

- **Transmitted path attenuation:** $f_0 = 300GHz$

$$a_{trans} = 20\log_{10}(\frac{c}{4\pi f_0}) - 20\log_{10}(d) - A_{pet}$$

$$= -81.98dB - 20\log 10(d[m]) - A_{pet}$$

Calibrated Attenuation due to PET

- **3 types of second order reflection:**

$$a_{i,\mathrm{Re}\,fl} = a_{trans} - \Delta a_{trans} - n_\tau(\tau_i - \tau_{trans}) + \Delta a_i$$

Different distribution models for different types of ref. path

Δa_{trans} : The offset compared with transmitted ray

n_τ : Slope along delay, Δa_i : Variation of fitting result

Case Study 1: Close Proximity Communications – Kiosk Downloading

D. Ray-based novel stochastic channel model

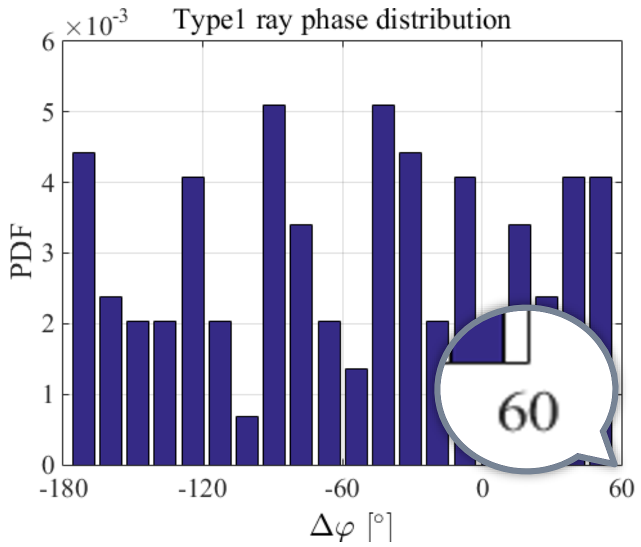
Parameter Extraction-Phase of Path

- **Transmitted path attenuation:**

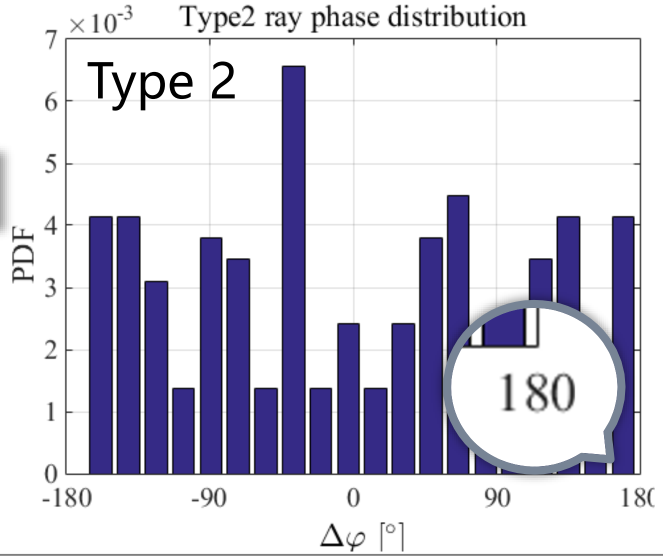
$$\varphi_{trans} = -2\pi f_0 \tau_{trans}$$

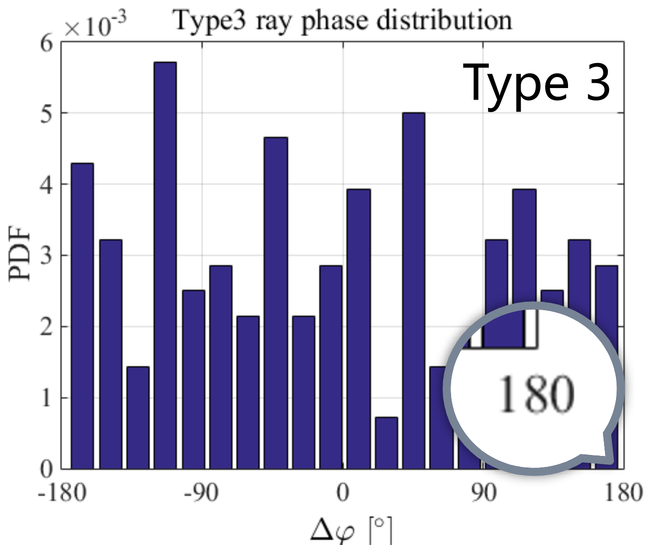
- **3 types of second order reflection:**

$$\varphi_{ref} = f(type)$$



- Type1:
  uniformly distributed between **-180** and **60**
- Type2 and Type 3:
  uniformly distributed between **-180** and **180**





Parameter Extraction-Frequency Dispersion

$$D_i(f) = \frac{f_0}{f^{\xi}} = 1$$

Should be extracted from RT simulation

Case Study 1: Close Proximity Communications – Kiosk Downloading

D. Ray-based novel stochastic channel model

Parameter Extraction - AOD and AOA

θ_{AOD} uniformly distributed between $-\arcsin(\frac{0.5W}{d_t})$ and $\arcsin(\frac{0.5W}{d_t})$

ϕ_{AOD} uniformly distributed between $-\arcsin(\frac{0.5H}{d_t})$ and $\arcsin(\frac{0.5H}{d_t})$

where W and H are the width and height of the front cover, respectively.
d_t is the distance between the TX and front cover.

θ_{AOA} and ϕ_{AOA} has strong geometrical relation with AOD, which can be obtained from the tilted angle of RX and the generated AOD.

Case Study 1: Close Proximity Communications – Kiosk Downloading

E. Realistic THz channel realization

Input

d: Distance between TX and RX in [m]

scenario: scenario type (1: all parallel, 2: pet tilted, 3: pet and RX metal tilted)

f: Frequency vector (f_start:f_step:f_stop)

Output

H: Channel matrix

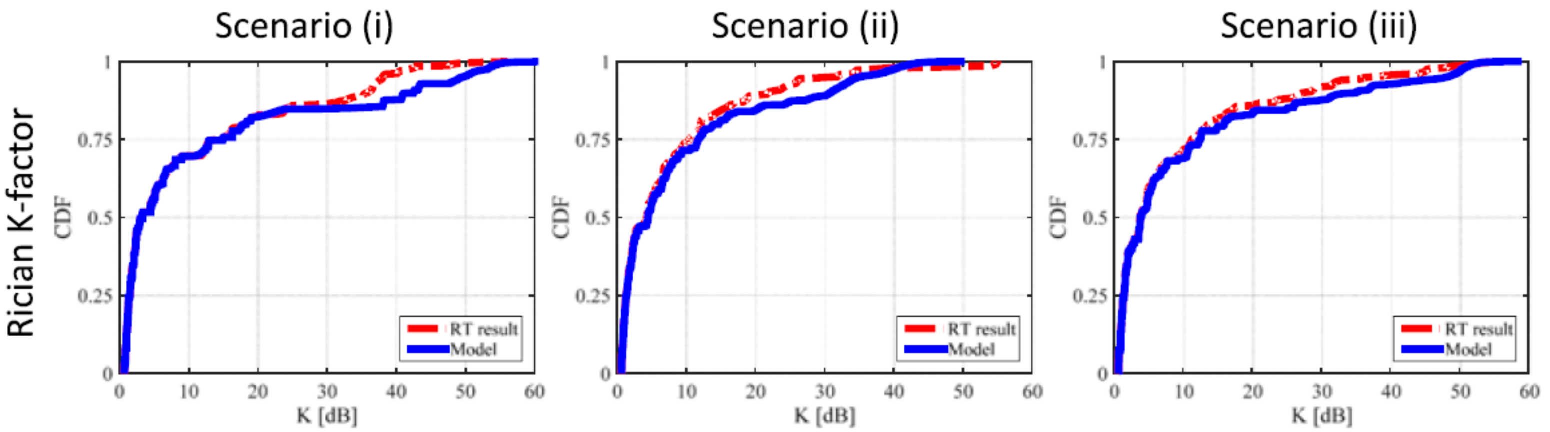
Reflection_Order: Reflection Count Vector

ToA: Time of Arrival Vector in ns

D: Dispersion Factor

AOA,AOD: Angle of arrival/departure

Comparison of Rician K-factor between the developed channel model and RT result



Danping He, **Ke Guan***, Alexander Fricke, *et al.*, "Stochastic Channel Modeling for Kiosk Applications in the Terahertz Band," ***IEEE Transactions on Terahertz Science and Technology***, vol. 7, no. 5, pp. 502-513, July 2017.

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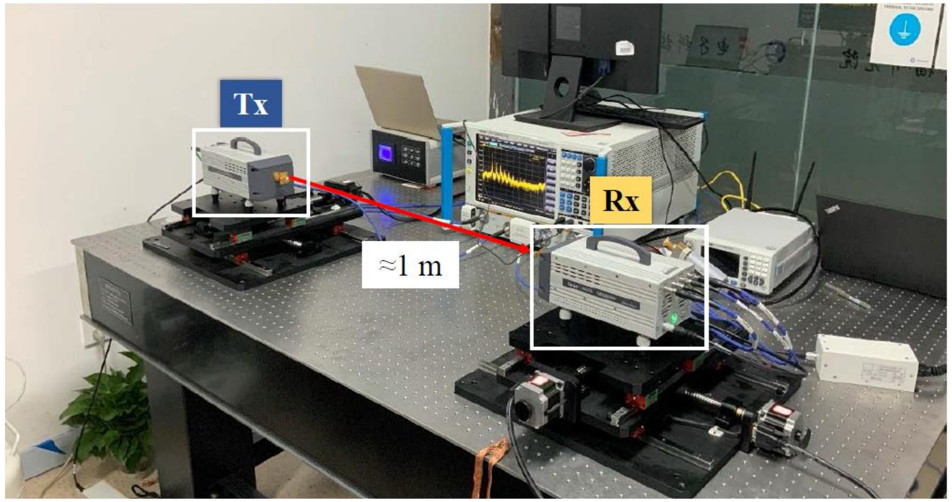
Case Study 2: Realistic THz Channel Modeling of Wireless Connections on a Desktop

A. Limited channel sounding

VNA-based Measurement

Frequency	330-365 GHz
Frequency points	5001
Frequency interval	7 MHz
IF bandwidth	1 kHz
Temporal resolution	0.029 ns
Spatial resolution	0.87 cm
Maximum excess delay	142.0 ns
Maximum path length	42.87 m

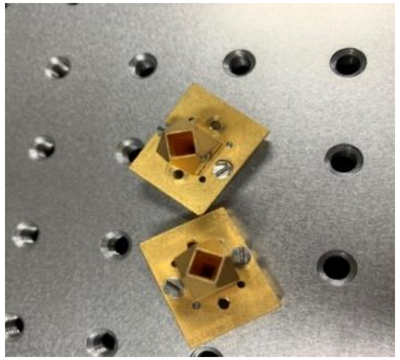
Measurement Scenario



Calibration method：

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

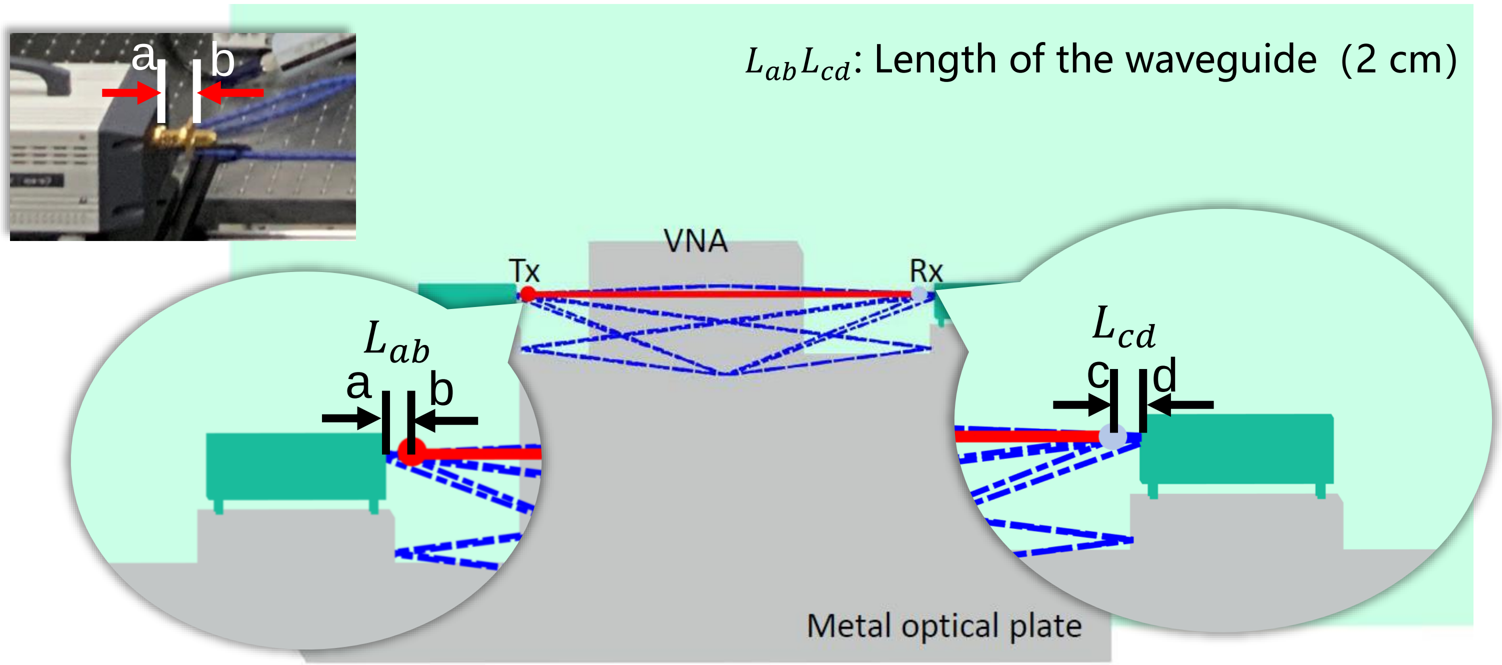
Measurement Antenna



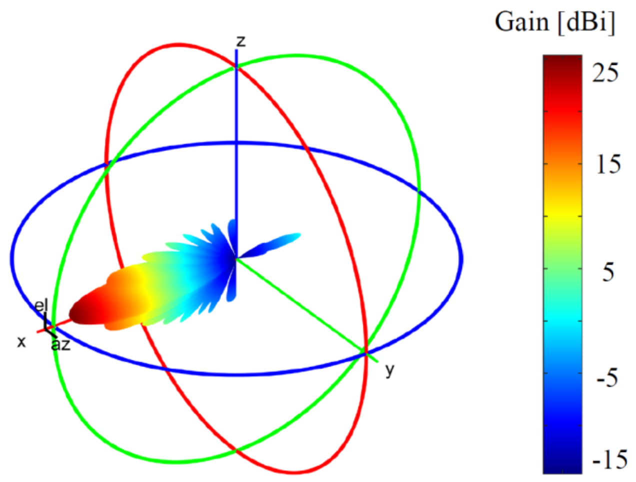
- **-Type：** VDI-WM-710
- **-Designation：** WR-2.8
- **-HPBW：** ≈10°
- **-Gain：** 25 dBi

Case Study 2: Realistic THz Channel Modeling of Wireless Connections on a Desktop

B. Calibration of RT simulator



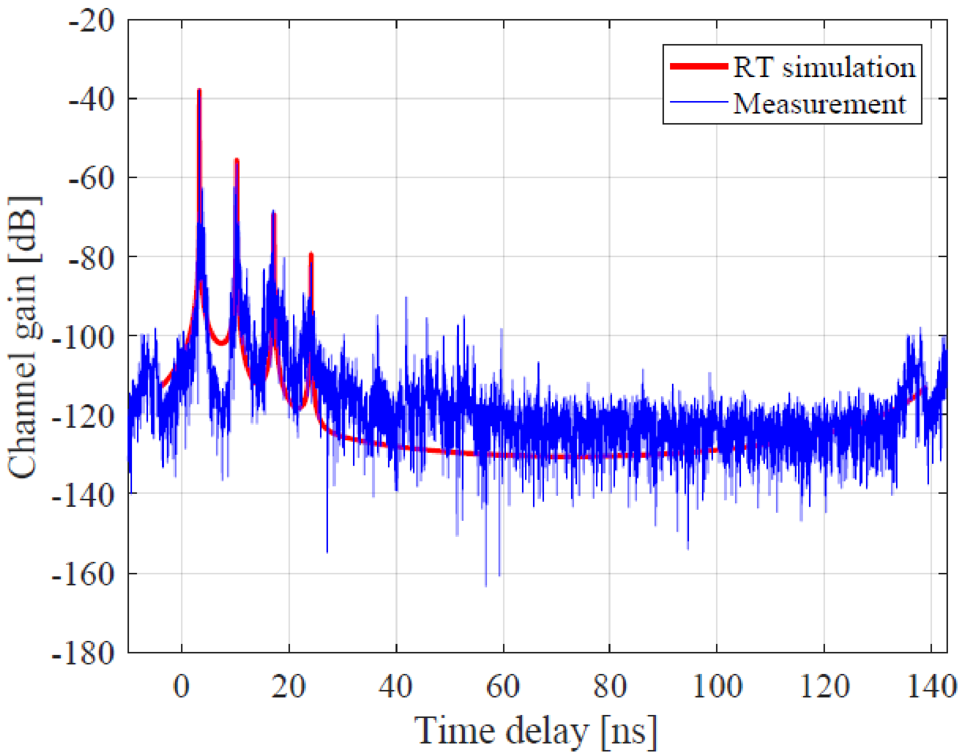
3D antenna pattern



- 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

Case Study 2: Realistic THz Channel Modeling of Wireless Connections on a Desktop

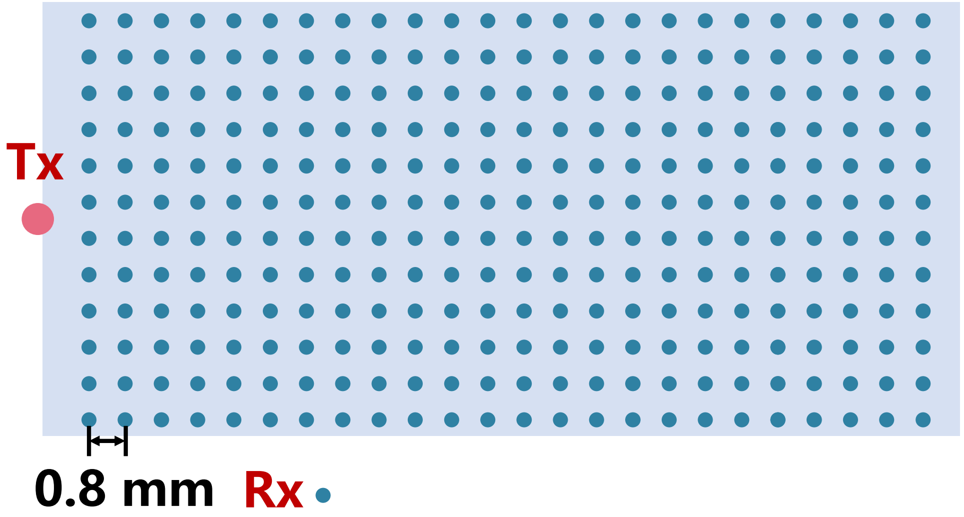
B. Calibration of RT simulator



- **LOS + multi-reflected rays**
- **Painted metal cannot be regarded as PEC**
- **Permittivity can be reversed by RT**
- **Painted metal:** ε' = 1.05 ε'' = 12.08
- **Mean absolute error: <1 dB in power; <0.1 ns in delay**

Case Study 2: Realistic THz Channel Modeling of Wireless Connections on a Desktop

C. Extensive RT simulations



- **Tx: fixed on the one side of the table**
- **Rx: the sampling interval is 0.8 mm, which is approximately equal to the wavelength of center frequency**
- **Full polarization combinations (VV, VH, HV, HH);**

Case Study 2: Realistic THz Channel Modeling of Wireless Connections on a Desktop

D. Cluster-based standard channel model families

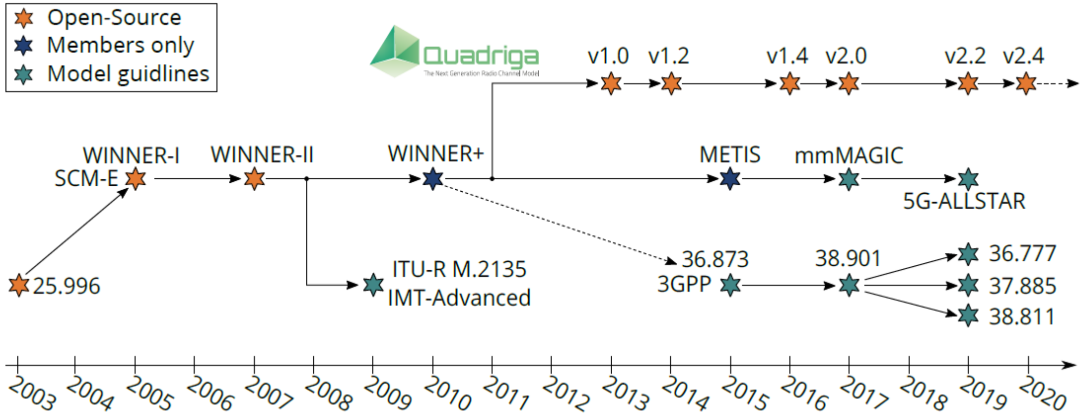
Key parameters of desktop THz channel

	SF [dB]	KF [dB]	DS [$\log_{10}([s])$]	ASD [$\log_{10}([°])$]	ASA [$\log_{10}([°])$]	ESD [$\log_{10}([°])$]	ESA [$\log_{10}([°])$]	XPR [dB]
μ_X	-	2.40	-9.13	1.88	1.88	1.06	1.06	7.11
σ_X	4.16	5.09	0.15	0.002	0.002	0.14	0.14	4.45

Per-cluster parameters for desktop channel

Parameter	SF	ASD	ESD	ASA	ESA
Value	4.29 dB	29.31°	7.31°	0.01°	0.02°

In line with 3GPP-like channel model families



QuaDRiGa

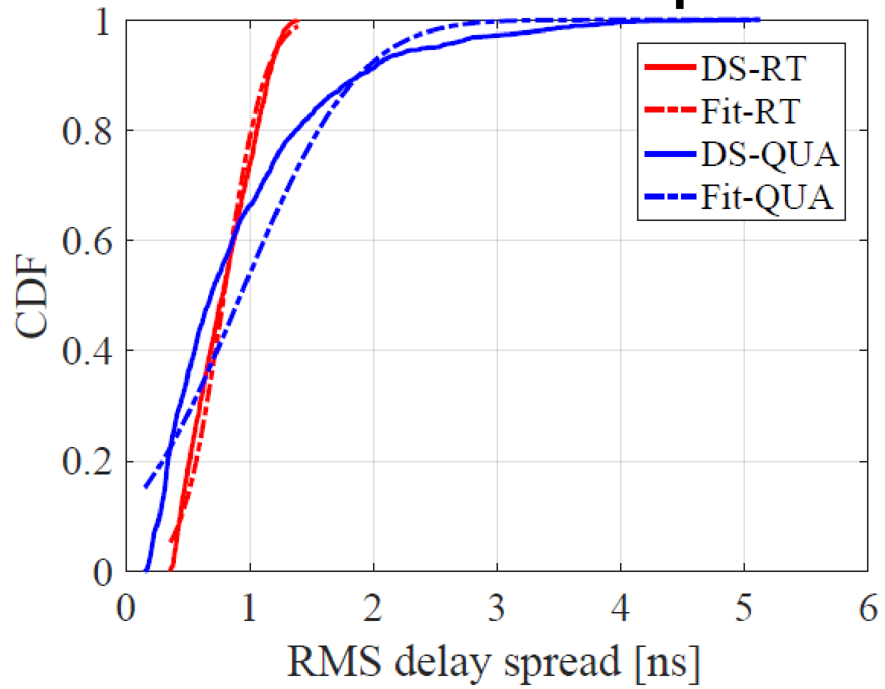
— 3GPP reference channel generator

— Geometry-based cluster channel modeling

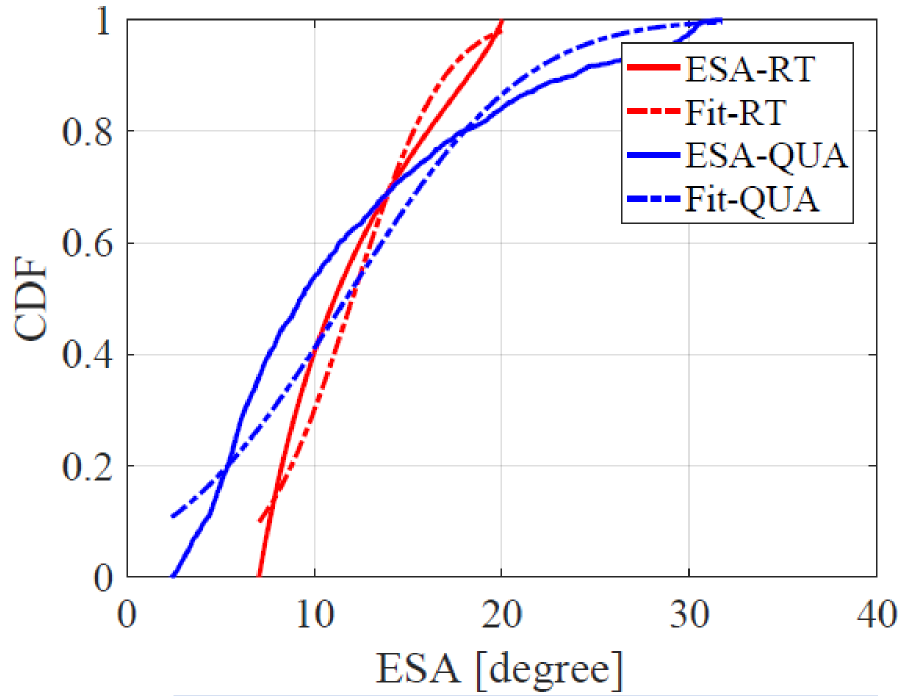
Case Study 2: Realistic THz Channel Modeling of Wireless Connections on a Desktop

E. Realistic THz channel realization

Comparison between QuaDRiGa and RT



Error of mean value: 0.14 ns



Error of mean value: 0.33°

- **There is no need to perform more complicated and time-consuming RT simulations. More channel data can be quickly generated using only the extracted channel parameters.**

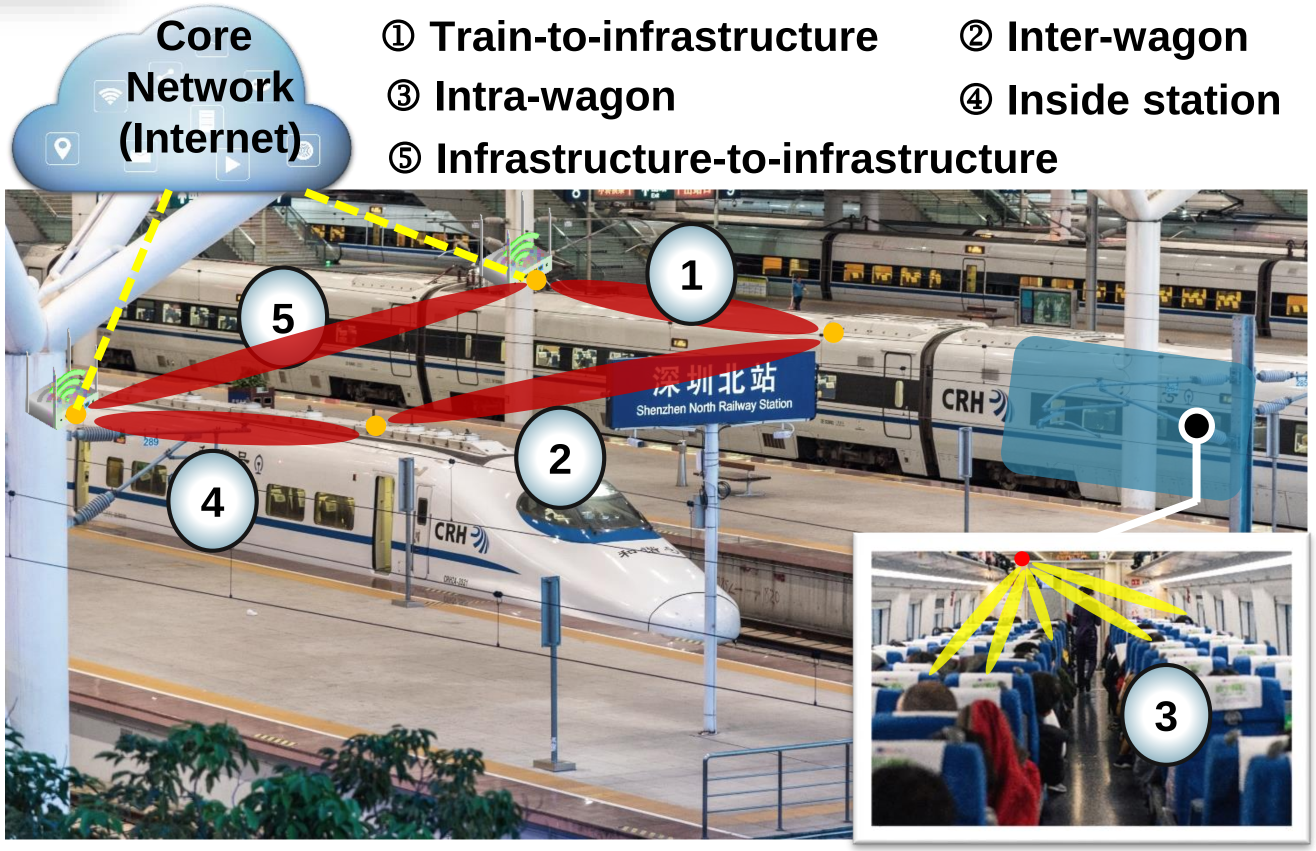
Outline

- Challenges on THz Channel Modeling
- New Paradigm of Realistic Terahertz Channel Modeling
- Three Use Cases from microscopy to macroscopy
  - Close-Proximity Communications
  - THz Communications on a desktop
  - **THz Channels for Smart Rail Mobility**
- Conclusion

Case Study 3: Realistic THz Channels for Smart Rail Mobility

Alexander von Humboldt Stiftung/Foundation

Characterization and Modeling for the Millimeter and Sub-Millimeter Wave MIMO Mobile Ultra-Broadband Channel enabling Smart Rail Mobility



<u>**Ke Guan**</u>, Guangkai Li, Thomas Kuerner, Andreas F. Molisch, Bile Peng, Ruisi He, Bing Hui, Junhyeong Kim, and Zhangdui Zhong, “On Millimeter Wave and THz Mobile Radio Channel for Smart Rail Mobility,” ***IEEE Transactions on Vehicular Technology***, vol. 66, no. 7, pp. 5658-5674, 2017. **(2019 ESI highly cited paper)**

Case Study 3: Realistic THz Channels for Smart Rail Mobility

Smart Rail Mobility Scenarios and High-Data Rate Applications therein

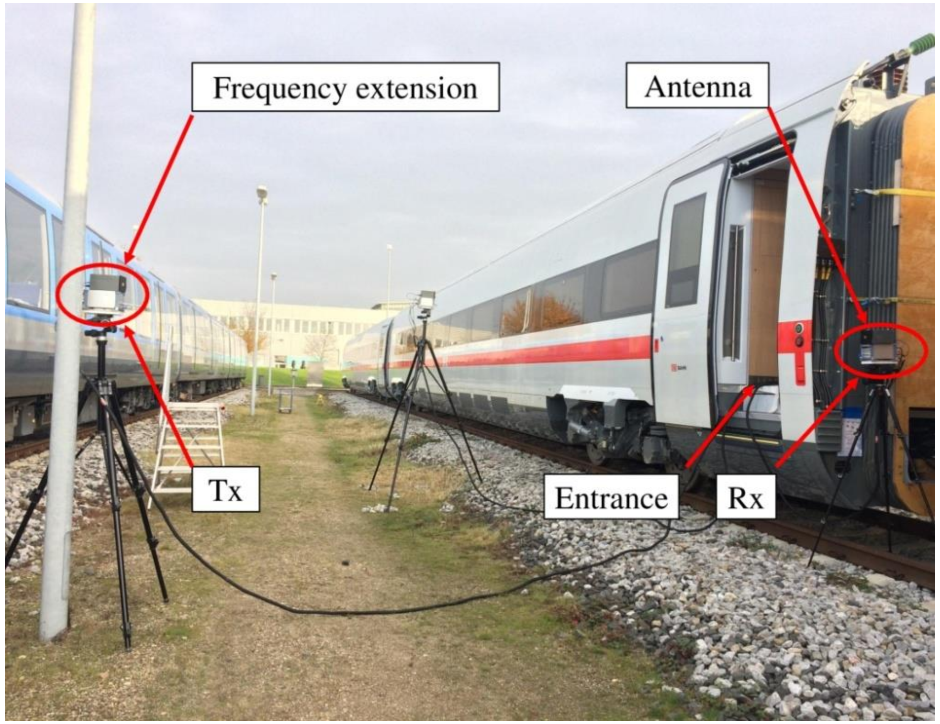
Smart rail mobility scenarios	On-board and wayside HD video surveillance	On-board real-time high-data rate connectivity	Train operation information	Real-time train dispatching HD video	Multimedia journey information
T2I	★	★	★	★	★
Inside station	★	★		★	★
T2T		★	★		★
I2I	★		★	★	★
Intra-wagon		★	★		★

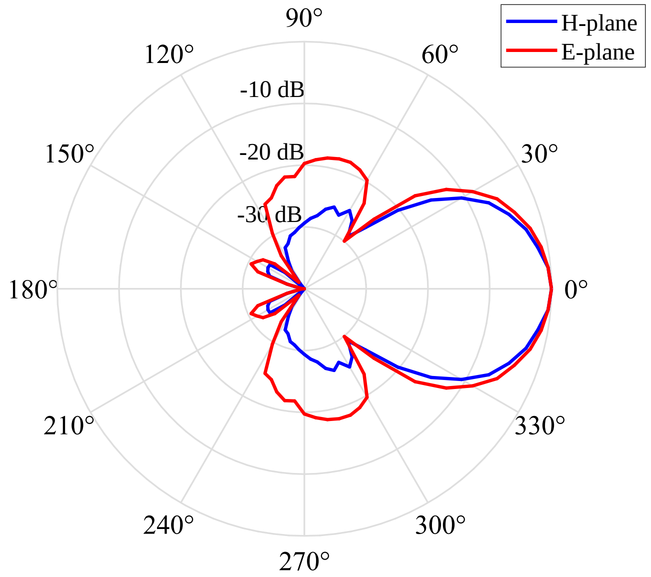
Bandwidth intensive applications – High definition video streams

Dozens of GHz bandwidths are required!

Case Study 3: Realistic THz Channels for Smart Rail Mobility

A. Limited channel sounding





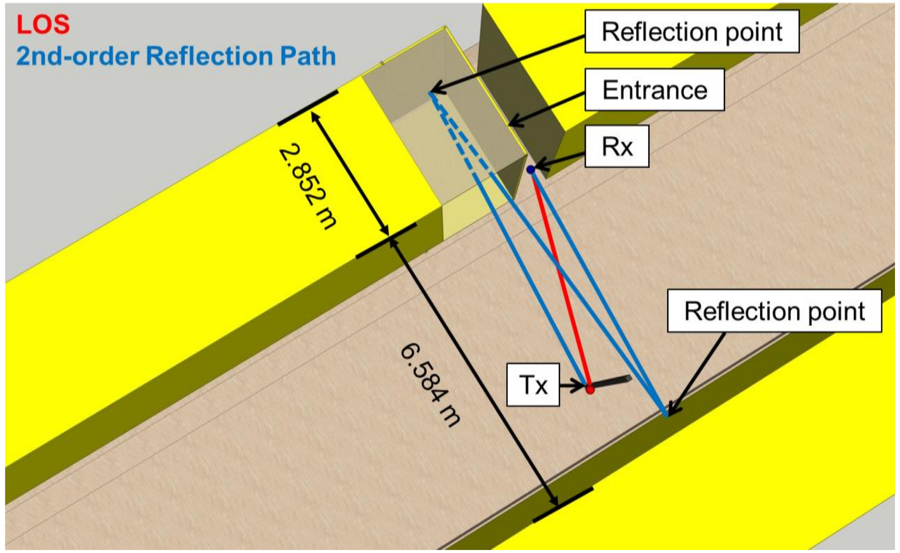
2D pattern of Tx and Rx antennas in the measurement

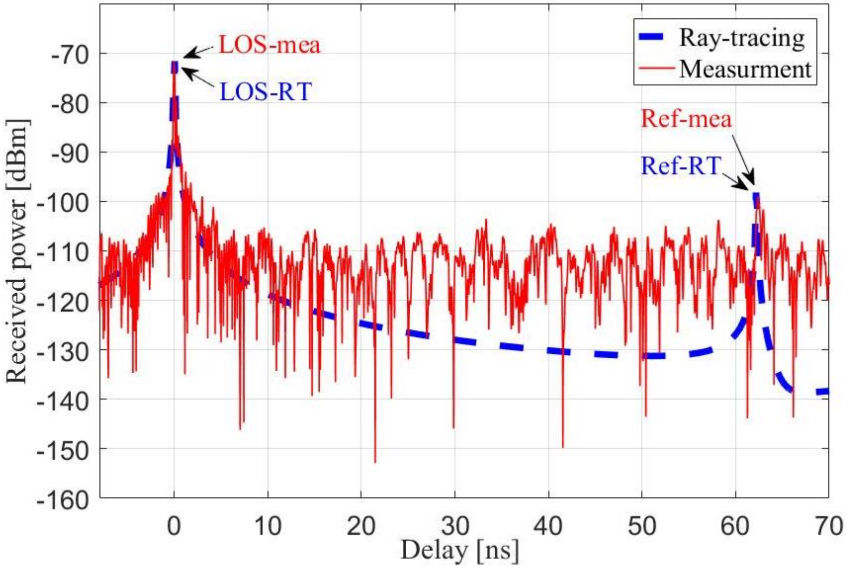
Measurement system	Bandwidth	Central frequency	Antenna type	Antenna gain	Antenna HPBW	Rician K-factor	RMS delay spread
	8 GHz	304.2 GHz	Directional	15 dBi	30°	3.52 dB	8.92 ns

Case Study 3: Realistic THz Channels for Smart Rail Mobility

B. Calibration of RT simulator

3D reconstructed model and traced rays





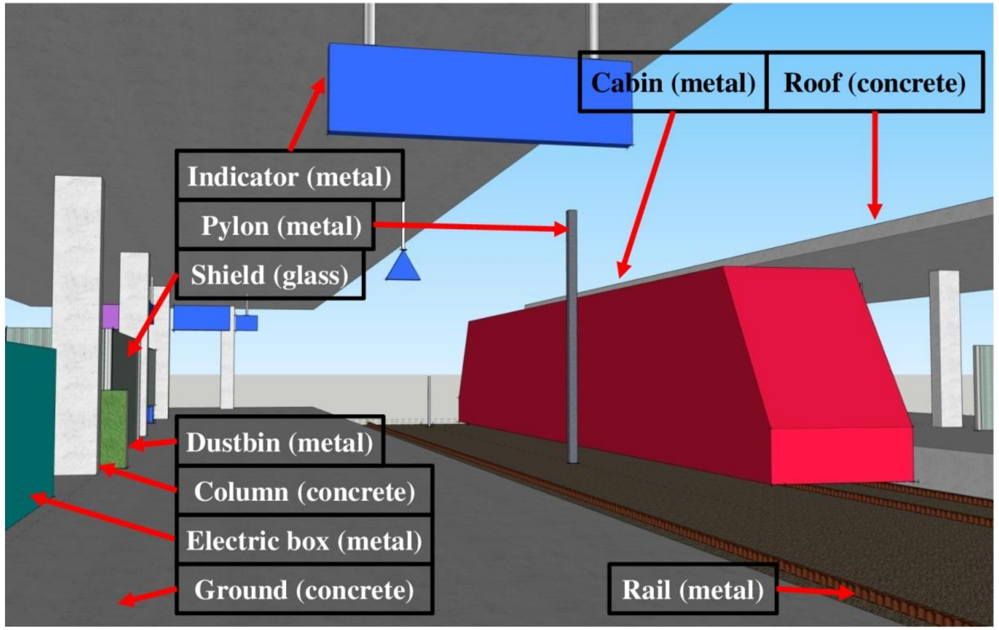
Validated reflection order
2

Path (Measurement)	LOS - mea	Ref- mea
Received power [dBm]	-71.66	-98.95
Delay [ns]	0.00	62.36

Path (Ray-tracing)	LOS - RT	Ref- RT
Received power [dBm]	-71.66	-98.21
Power error [dB]	0.00	0.74
Delay [ns]	0.00	62.17
Delay error [ns]	0.00	0.19

Case Study 3: Realistic THz Channels for Smart Rail Mobility

C. Extensive RT simulations

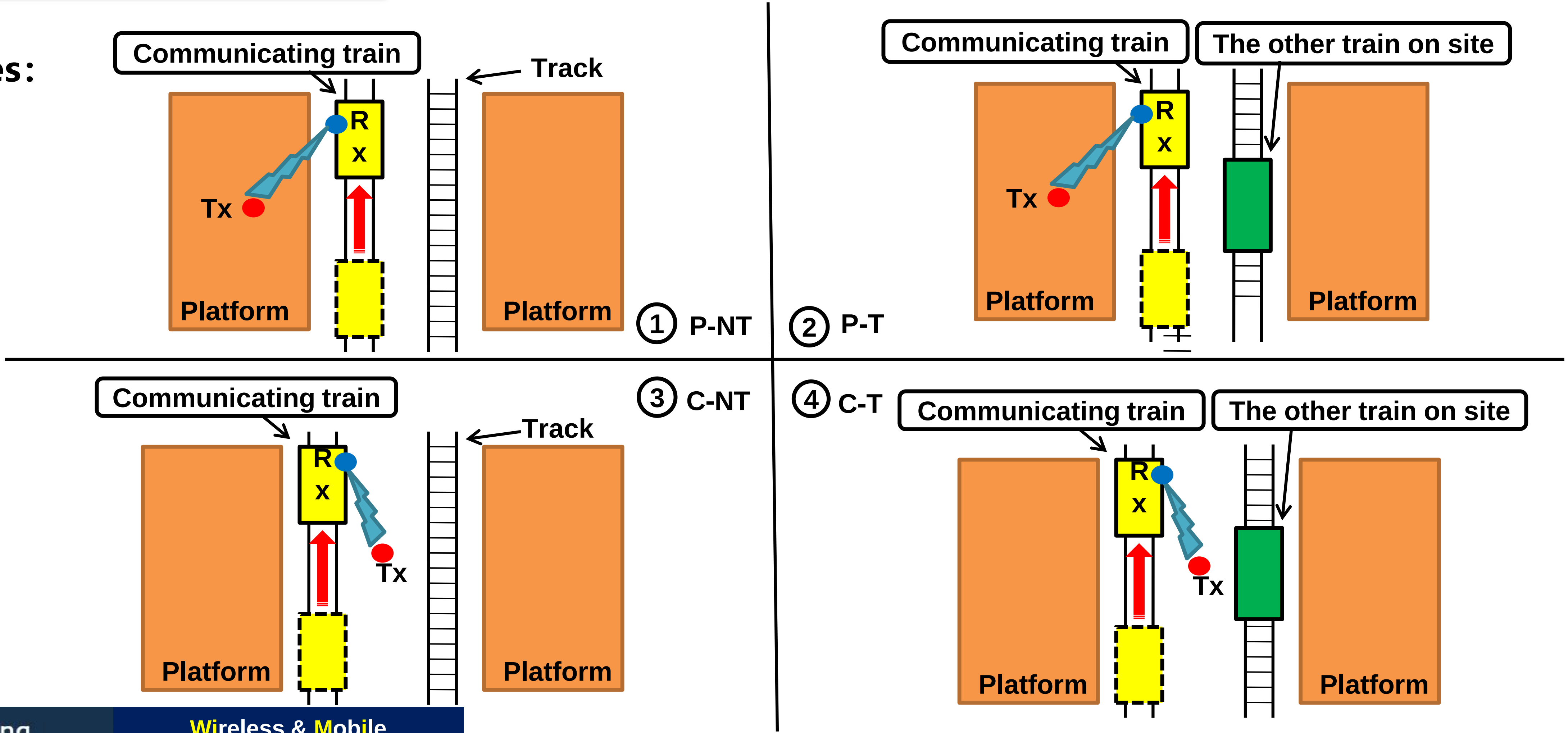


Polarization	**VV, VH, HH, and HV**
Antenna type	**Isotropic**
Antenna gain and Tx power	**0 dBi and 0 dBm**
Frequency range	**300-308 GHz**
Propagation mechanism	**LOS + 2nd order of reflection + scattering**

Case Study 3: Realistic THz Channels for Smart Rail Mobility

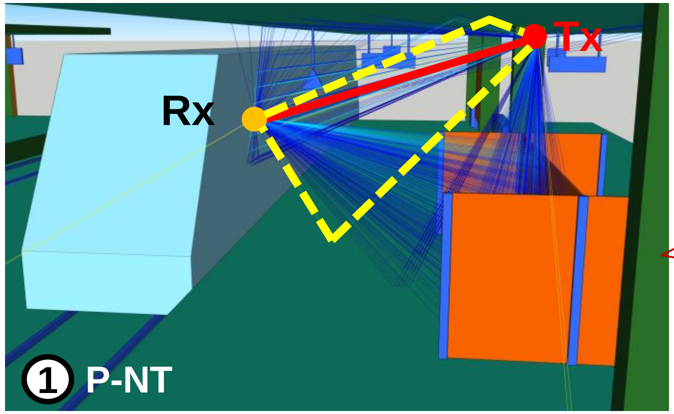
C. Extensive RT simulations

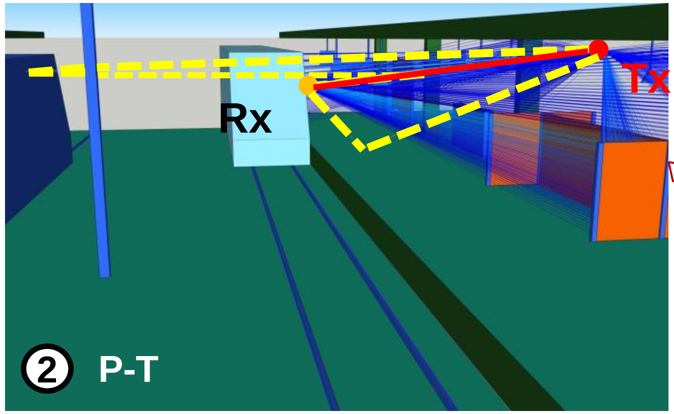
Four Cases:

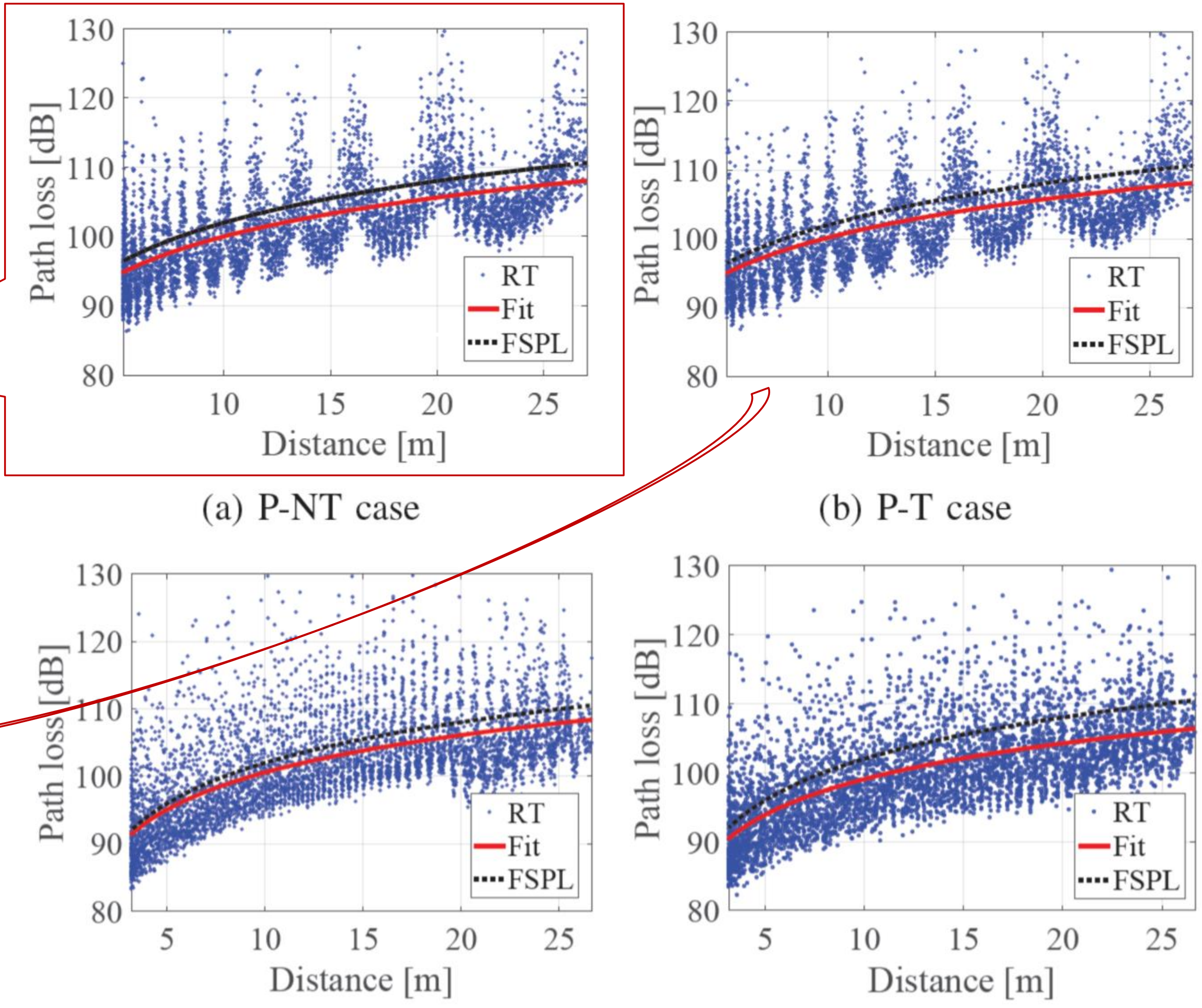


Case Study 3: Realistic THz Channels for Smart Rail Mobility

C. Extensive RT simulations



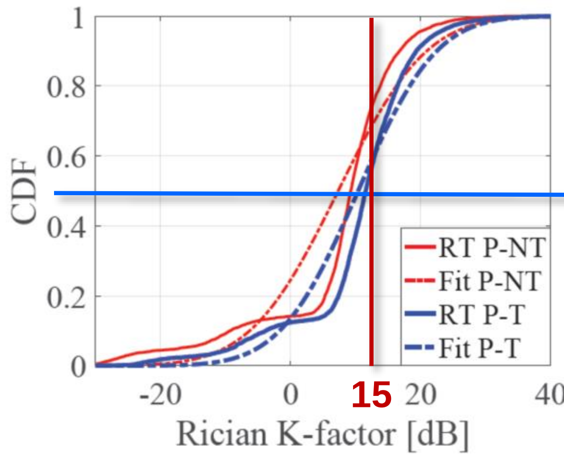




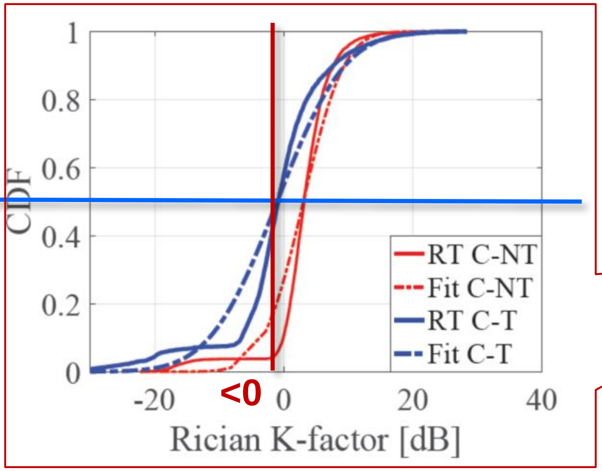
(a) P-NT case (b) P-T case

(c) C-NT case (d) C-T case

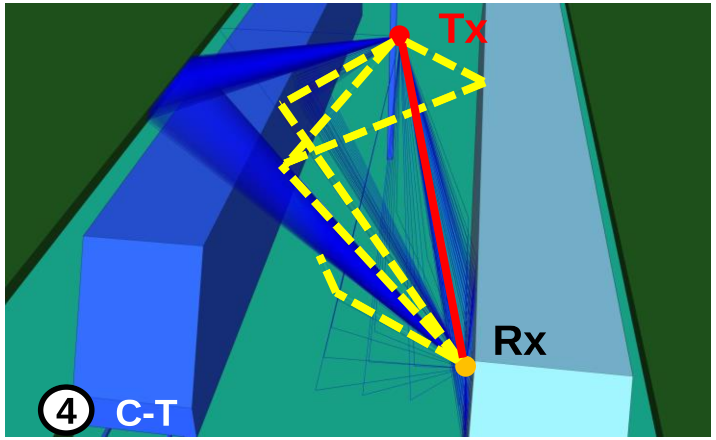
Case Study 3: Realistic THz Channels for Smart Rail Mobility

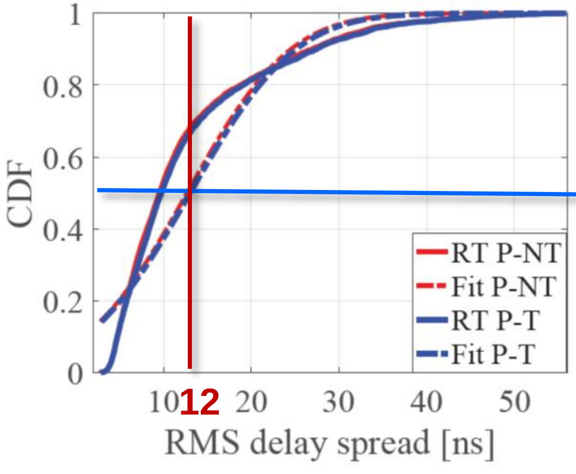


(a) P-NT and P-T cases

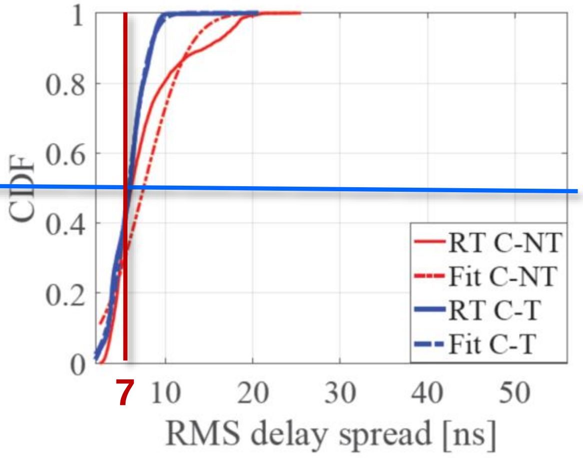


(b) C-NT and C-T cases





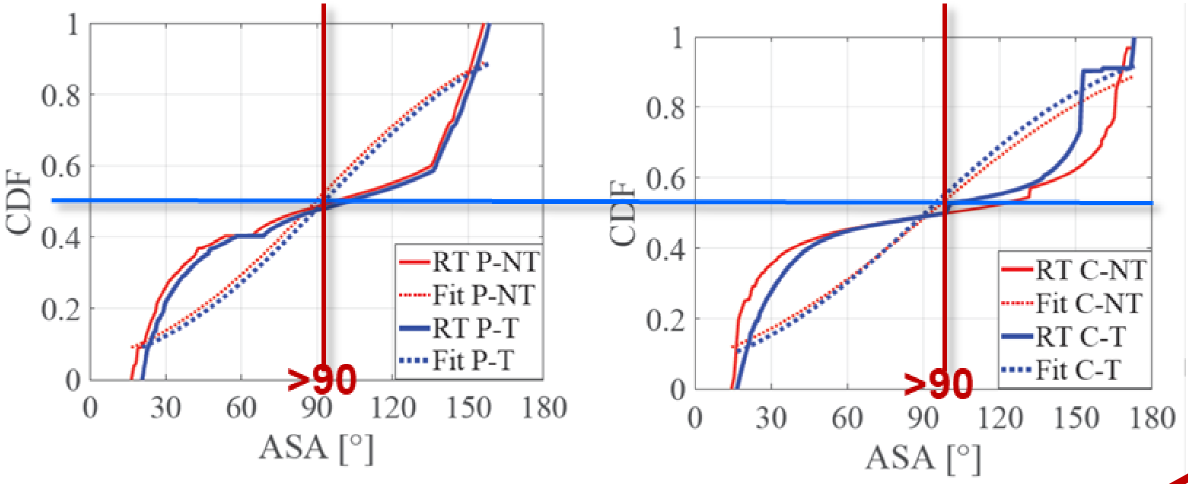
(a) P-NT and P-T cases



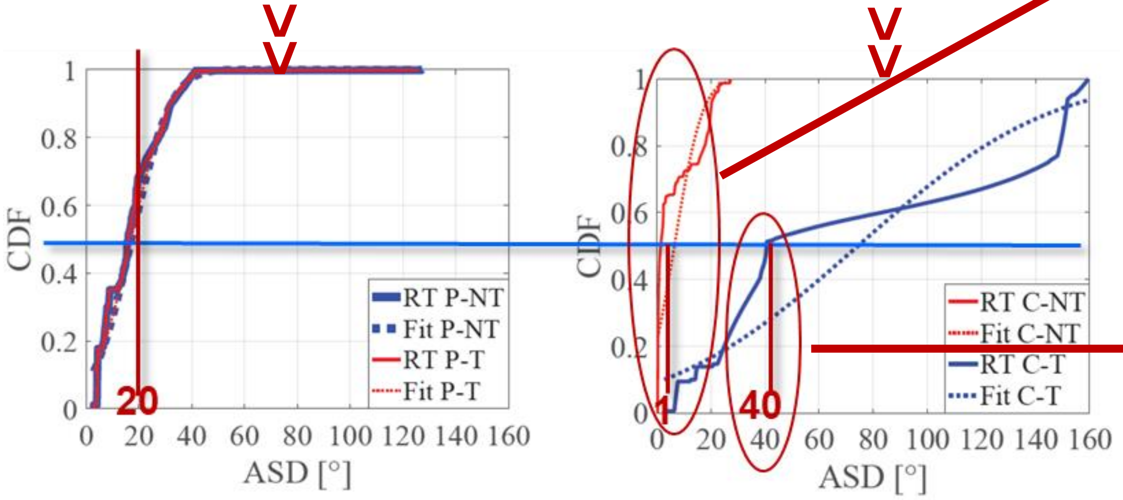
(b) C-NT and C-T cases

- Much **stronger multipaths** can be received when the **Tx** is deployed on the **catenary mast**.
- The **reflection attenuation** caused by **metallic** train body is **trivial**, and therefore, considerably **decrease the KF**.

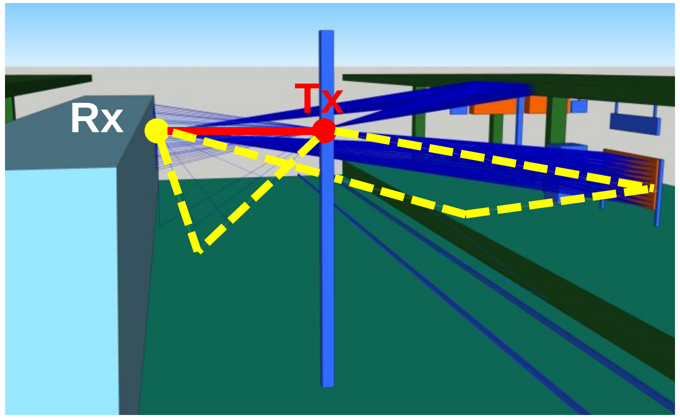
Case Study 3: Realistic THz Channels for Smart Rail Mobility



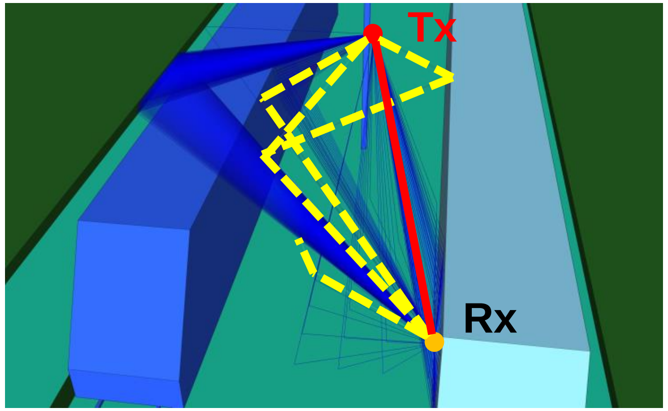
(a) P-NT and P-T cases (b) C-NT and C-T cases



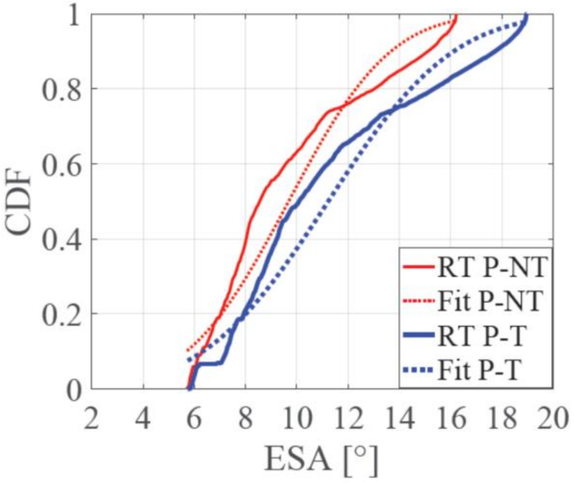
(a) P-NT and P-T cases (b) C-NT and C-T cases



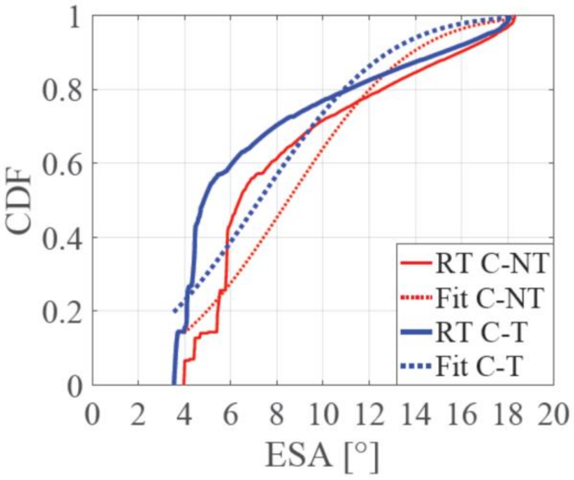
The **other train** generates **strong multipaths** to **increase** the **ASD**.



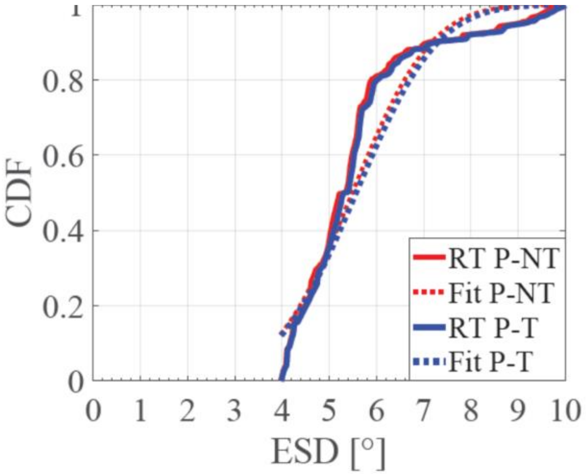
Case Study 3: Realistic THz Channels for Smart Rail Mobility



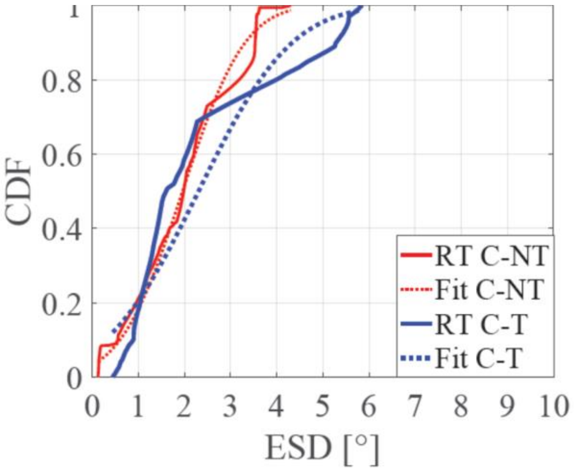
(a) P-NT and P-T cases



(b) C-NT and C-T cases



(a) P-NT and P-T cases



(b) C-NT and C-T cases

- The **ESA and ESD** are much **smaller** than those in the azimuth plane.
- This means that if the Tx and Rx are vertically polarized and with the similar heights which are relatively high from the platform or ground, **most of the multipaths** will be generated on the **azimuth plane**, which has potential to offer more **diversity gain** to the **MIMO** system.

Case Study 3: Realistic THz Channels for Smart Rail Mobility

D. Cluster-based standard channel model families

Channel Case	T2I inside station			
	P-NT	P-T	C-NT	C-T
A	18.65	18.41	18.34	17.25
B	81.35	81.75	82.24	81.80
σ_{SF} [dB]	5.22	5.37	5.85	5.47
λ_{SF} [m]	0.02	0.02	0.02	0.02
μ_{KF} [dB]	7.30	10.37	3.04	-1.01
σ_{KF} [dB]	10.63	9.43	4.95	8.21
λ_{KF} [m]	0.25	0.25	0.25	0.25
μ_{DS} [$\log_{10}([s])$]	-7.99	-7.98	-8.18	-8.26
σ_{DS} [$\log_{10}([s])$]	0.27	0.27	0.20	0.16
λ_{DS} [m]	0.23	0.23	0.24	0.25
r_{DS}	1.45	1.38	0.81	0.76

Stochastic Channel Generators, such as 3GPP, Quadriga, etc

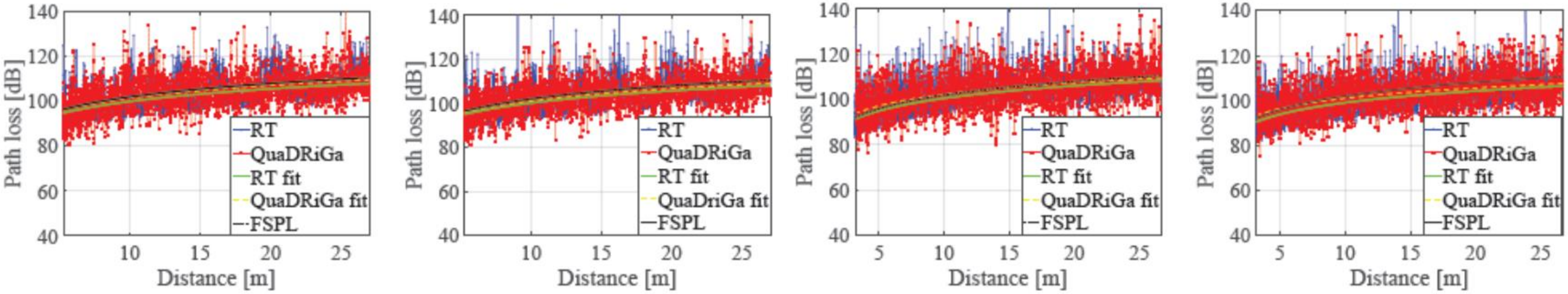
Quadriga
The Next Generation Radio Channel Model

Channel Case	T2I inside station			
	P-NT	P-T	C-NT	C-T
μ_{ASD} [$\log_{10}([°])$]	1.12	1.13	0.33	1.70
σ_{ASD} [$\log_{10}([°])$]	0.32	0.32	0.69	0.43
λ_{ASD} [m]	0.25	0.25	0.25	0.25
μ_{ESD} [$\log_{10}([°])$]	0.73	0.74	0.18	0.27
σ_{ESD} [$\log_{10}([°])$]	0.09	0.09	0.38	0.29
λ_{ESD} [m]	0.25	0.25	0.25	0.25
μ_{ASA} [$\log_{10}([°])$]	1.83	1.86	1.79	1.82
σ_{ASA} [$\log_{10}([°])$]	0.35	0.32	0.43	0.37
λ_{ASA} [m]	0.25	0.25	0.25	0.25
μ_{ESA} [$\log_{10}([°])$]	0.96	1.02	0.88	0.80
σ_{ESA} [$\log_{10}([°])$]	0.13	0.14	0.20	0.23
λ_{ESA} [m]	0.25	0.25	0.25	0.25
μ_{XPR} [dB]	3.05	3.10	5.90	8.53
σ_{XPR} [dB]	1.89	1.86	1.81	2.32
Per-cluster parameter				
Cluster number	5	5	5	5
SF [dB]	10.36	8.86	11.13	8.31
ASD [°]	4.63	5.16	1.71	10.46
ESD [°]	3.50	3.36	1.55	1.43
ASA [°]	17.83	16.85	16.90	15.67
ESA [°]	11.07	12.26	10.27	6.45

Case Study 3: Realistic THz Channels for Smart Rail Mobility

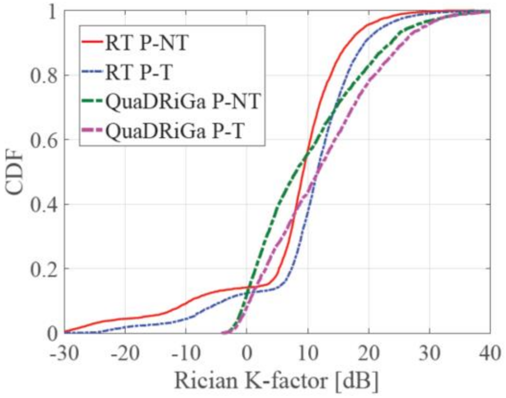
E. Realistic THz channel realization

Path loss and shadow fading (QuaDRiGa vs RT)

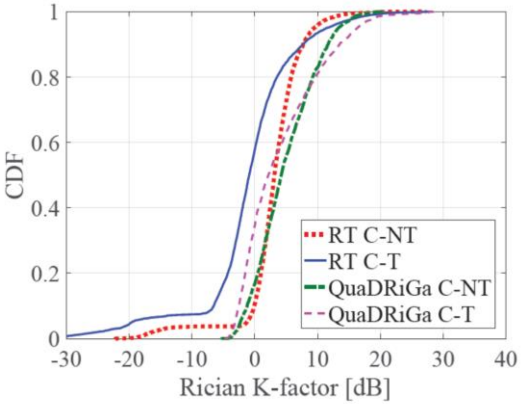


(a) P-NT case of T2I (b) P-T case of T2I (c) C-NT case of T2I (d) C-T case of T2I

CDF of Rician K-factor for P-NT and P-T cases (QuaDRiGa vs RT)



CDF of Rician K-factor for C-NT and C-T cases (QuaDRiGa vs RT)



Ke Guan, Bile Peng, Danping He, Johannes M. Eckhardt, Sebastian Rey, Bo Ai, Zhangdui Zhong, and Thomas Kuerner, "Measurement, Simulation, and Characterization of Train-to-Infrastructure Inside-Station Channel at the Terahertz Band," ***IEEE Transactions on Terahertz Science and Technology***, vol. 9, no. 3, pp. 291-306, 2019.

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- **Conclusion**

Conclusion

- Empirical channel model or stochastic channel model, which is based on large amounts of measurement data, no longer stands in THz channel modeling.
- The novel paradigm for THz channel modeling can break through the bottleneck of scarce full-dimensional channel sounding measurements.
- The novel paradigm is with the core of high-performance RT (http://raytracer.cloud).
- The channel modeling approach aims to streamline the design, simulation, and development of 6G THz communication systems.

Thank you
for your attention

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