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

Submission Title: THz Channel Sounding and Characterization for Smart Rail Mobility in the Era of 6G
Date Submitted: 15 March 2021
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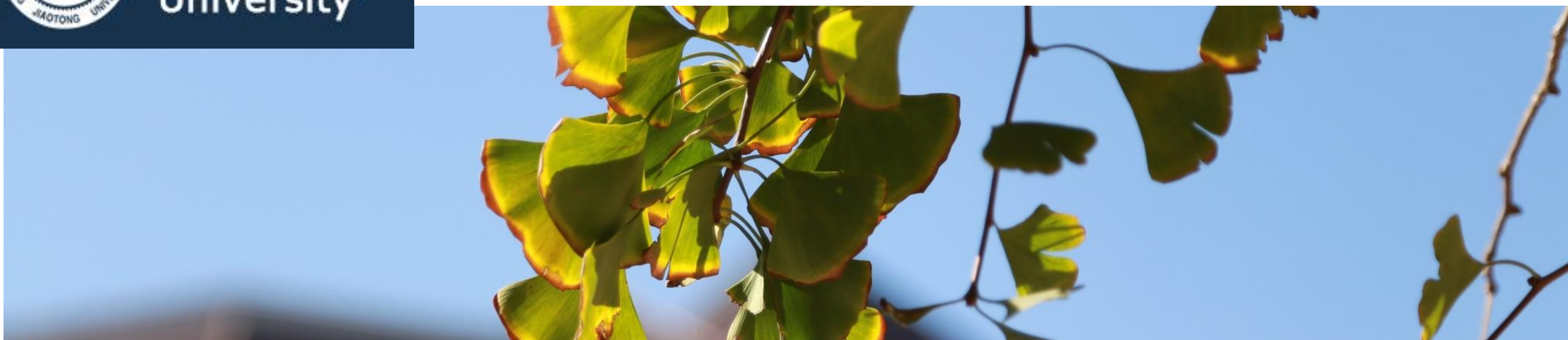
Re: n/a

Abstract: In this document, the smart rail mobility channel is characterized through channel sounding and ray tracing at 300 GHz band with an 8 GHz bandwidth in the Intra-wagon and Inside station scenarios. Corresponding channel characteristics such as large-scale fading, Rician K-factor, delay spread, azimuth/elevation angular spread of arrival/departure, and cross-polarization ratio are extracted. The results provide valuable insights into the system design and evaluation for THz communication enabled Smart Rail Mobility.

Purpose: Information of IEEE 802.15 SC THz

Beijing Jiaotong University

Wireless & Mobile Communication for Rail Transportation (WiMiRT)



THz Channel Sounding and Characterization for Smart Rail Mobility in the Era of 6G

Ke Guan[1], Danping He[1], Bo Ai[1], Haofan Yi[1], Bile Peng[2], Zhengrong Lai[3], Jianwu Dou[4], Zhangdui Zhong[1], and Thomas Kuerner[2]

[1] Beijing Jiaotong University, [2] Technische Universität Braunschweig, [3] Guangdong Communications & Networks Institute, [4] ZTE Corporation

This work is supported by the Key-Area Research and Development Program of Guangdong Province, China (2019B010157001), the NSFC under Grant (61771036, U1834210, 61901029, and 61725101), State Key Lab of Rail Traffic Control and Safety Project under Grant RCS2020ZZ005, Alexander von Humboldt Foundation, and the ZTE Corporation.

Outline

1. **Motivation of Smart Rail Mobility enabled by THz**
2. **Challenge and New Paradigm for THz Mobile Channel Modeling**
   - **Channel Sounding**
   - **Ray Tracing**
3. **THz Channel Characterization for**
   - **Intra-wagon Scenario**
   - **Inside Station**
4. **Conclusion**

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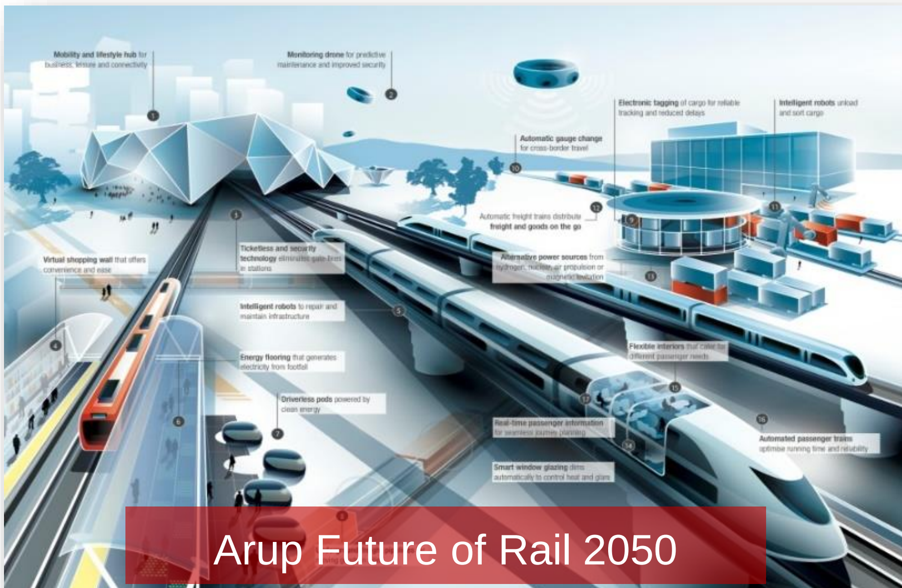
Why Smart Rail Mobility?

- **Horizon 2020**: one part of the objective of **Smart, green and integrated transport**:
- Rail traffic is highly expected to evolve into a new era of "**smart rail mobility**" to achieve **optimized mobility, higher safety, and lower costs**.



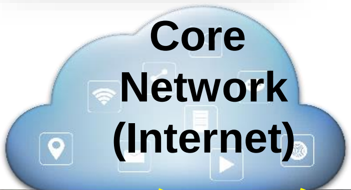
This vision → A seamless high-data rate wireless connectivity for railway

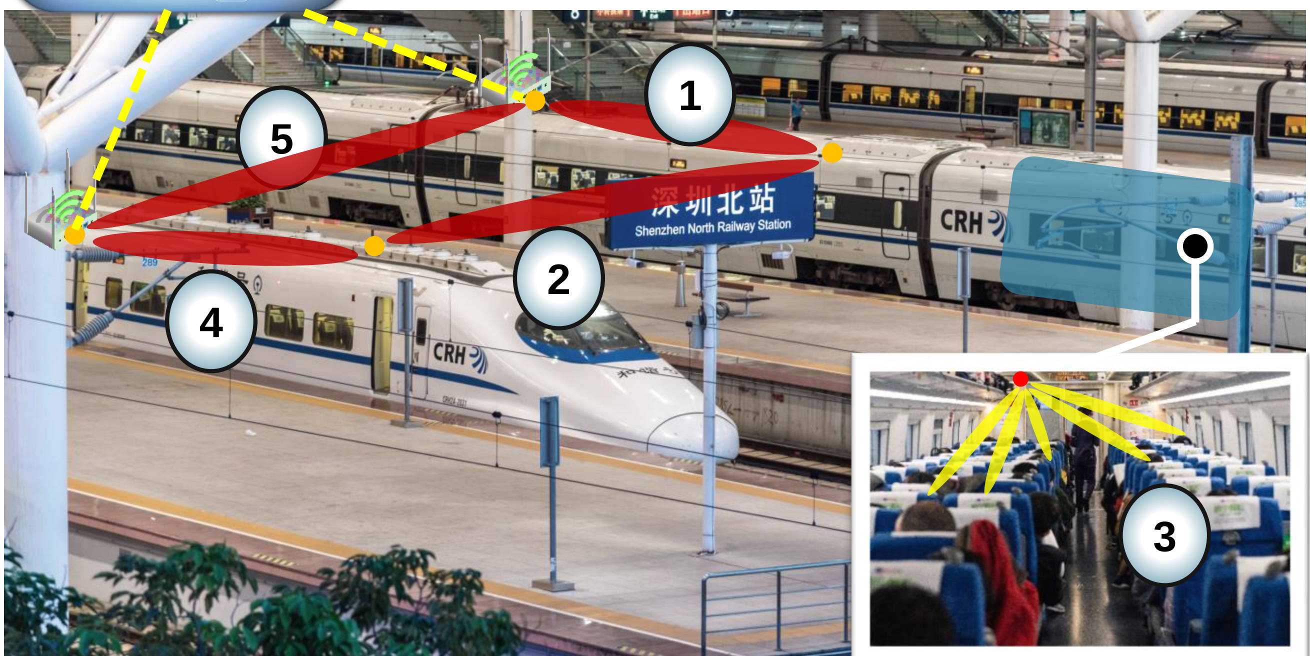
Why THz Bands?

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

Alexander von Humboldt
Stiftung/Foundation

① Train-to-infrastructure **② Inter-wagon**
③ Intra-wagon **④ Inside station**
⑤ Infrastructure-to-infrastructure





<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. **(ESI highly cited paper)**

Why THz Bands?

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!

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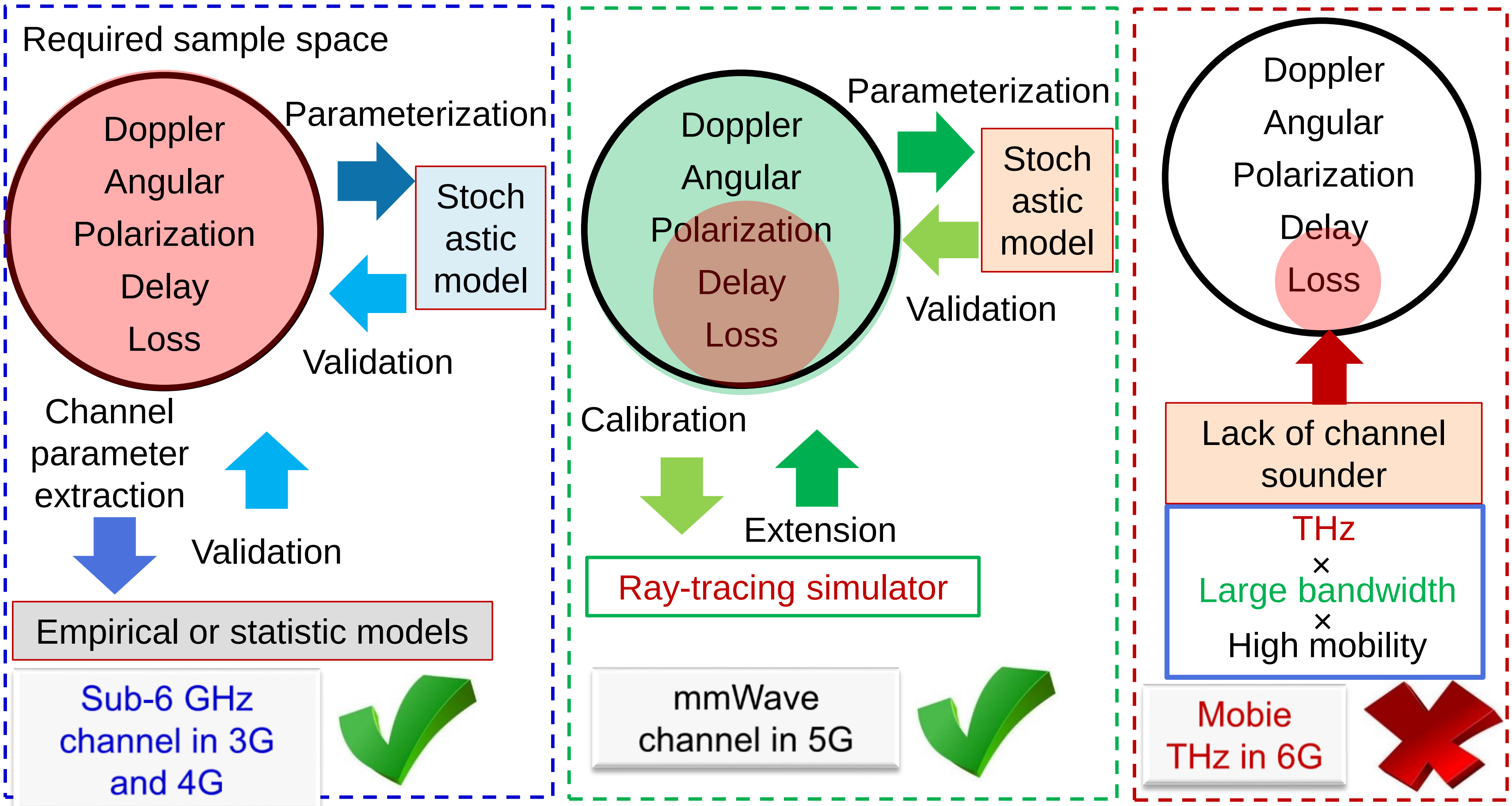
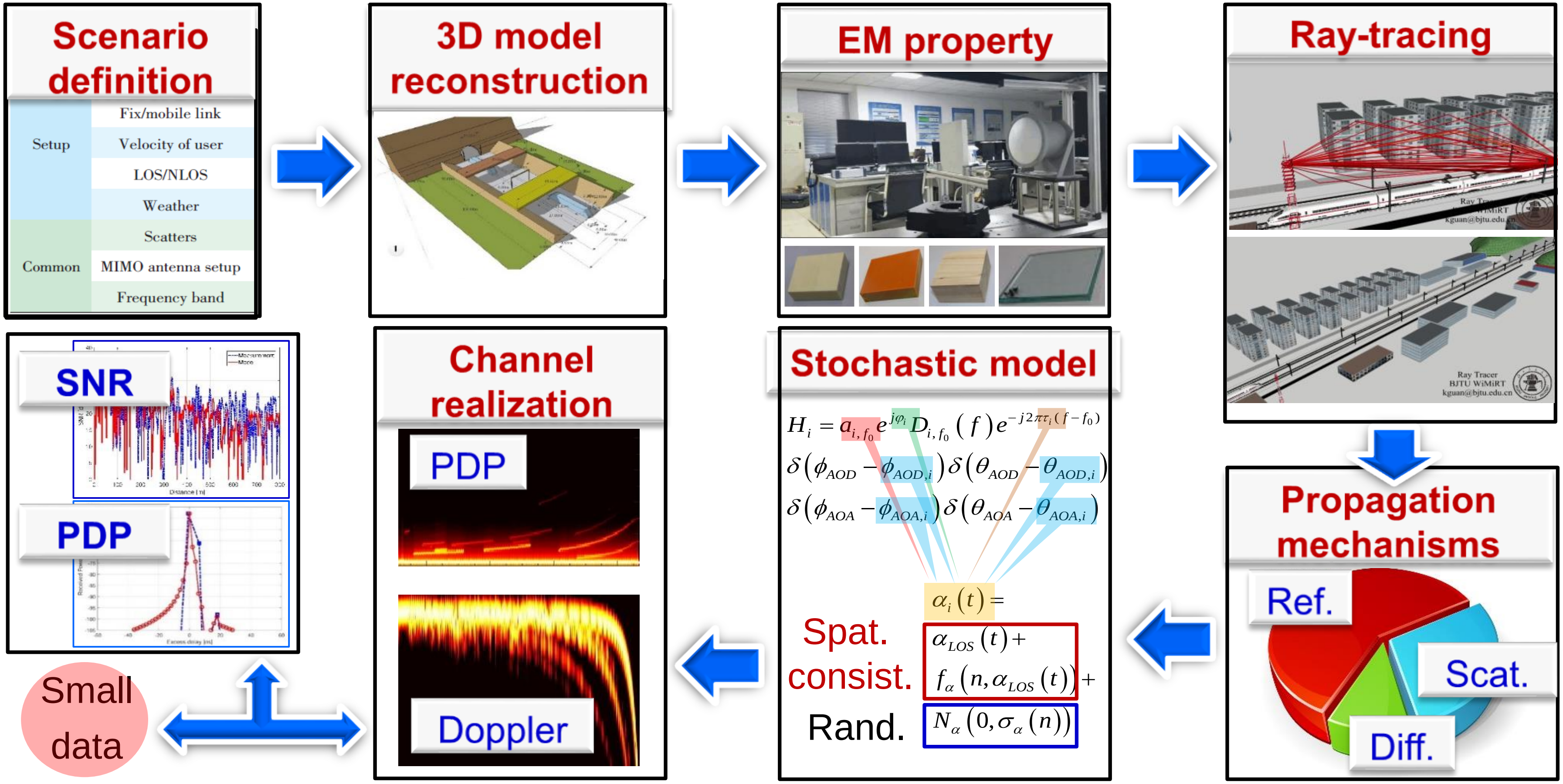
Challenges on Channel Modeling



New paradigm is needed!

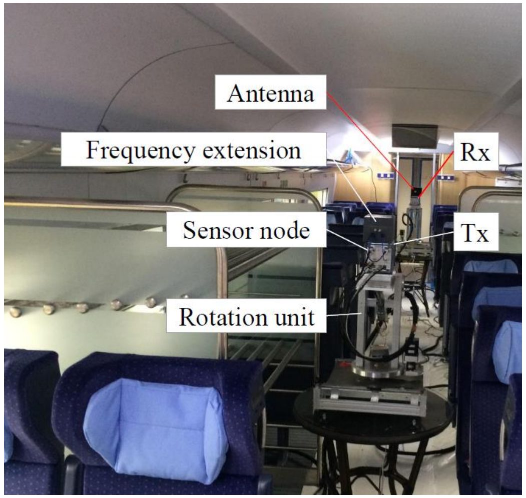
New Paradigm for Channel Modeling



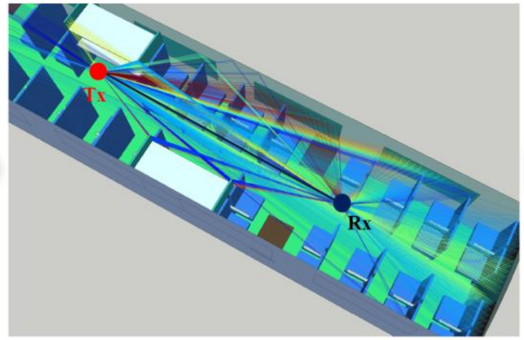
<u>**Ke Guan**</u>, et al., "Towards Realistic High-Speed Train Channels at 5G Millimeter-Wave Band – Part I: Paradigm, Significance Analysis, and Scenario Reconstruction," ***IEEE Transactions on Vehicular Technology***, vol. 67, no. 10, pp. 9112-9128, 2018. **(IEEE VTS 2019 Neal Shepherd Memorial Award)**

Research Paradigm of THz Channel Modeling

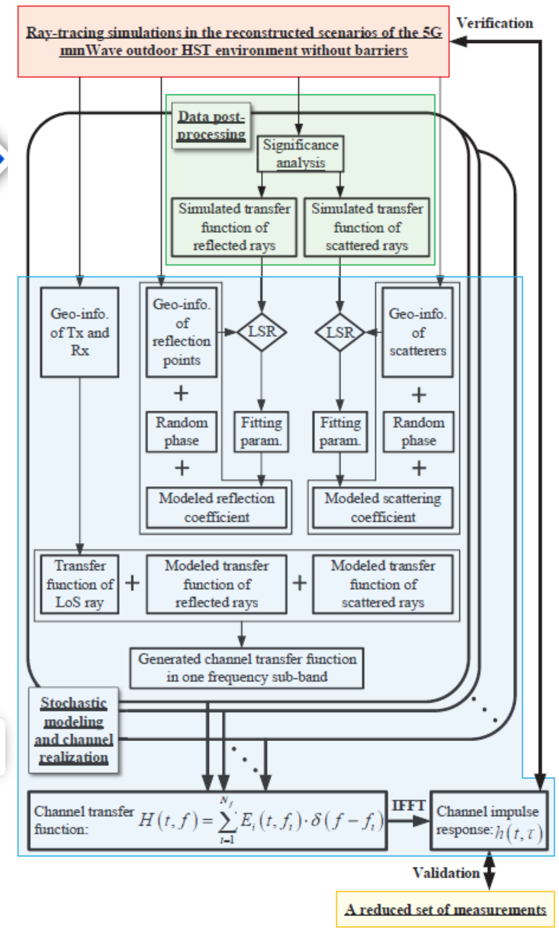
Channel sounding



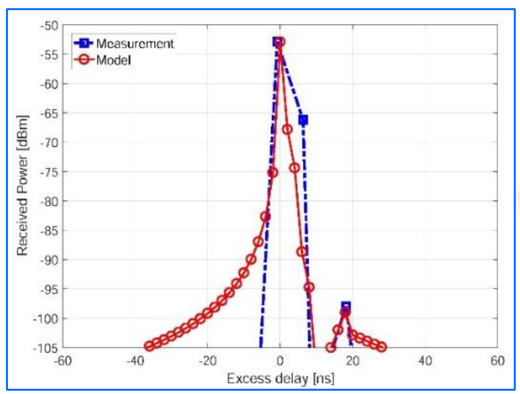
Extensive ray-tracing



Stochastic modeling



Channel realization



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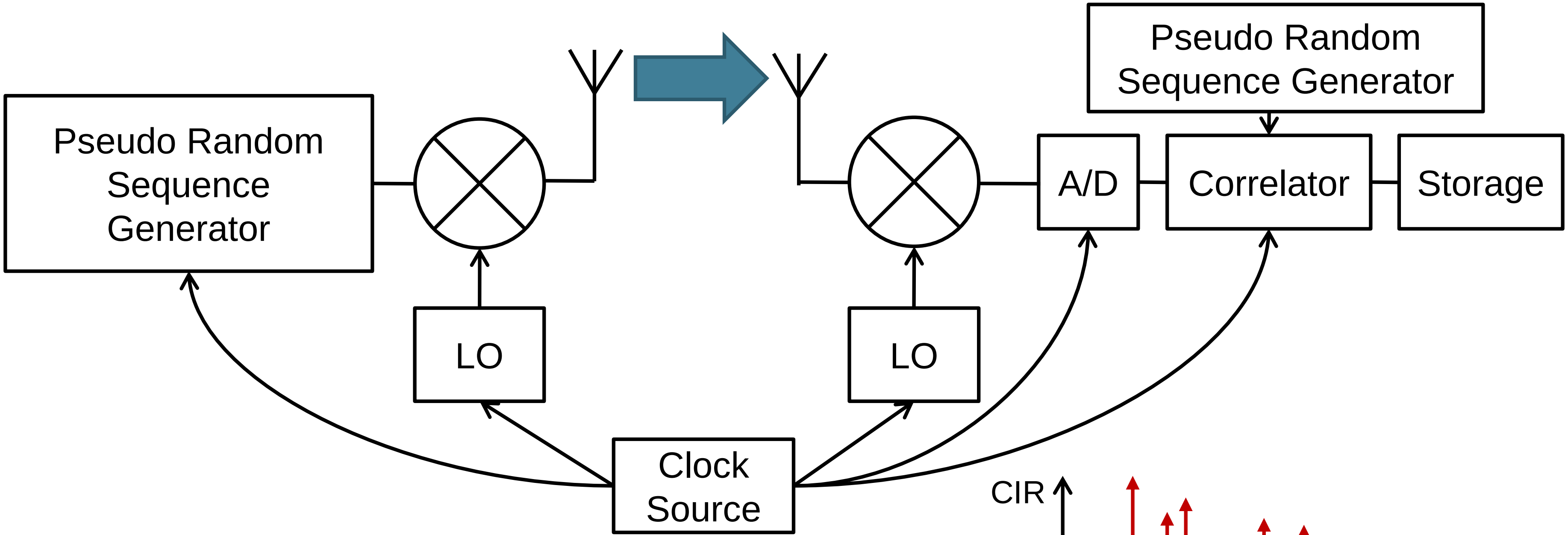
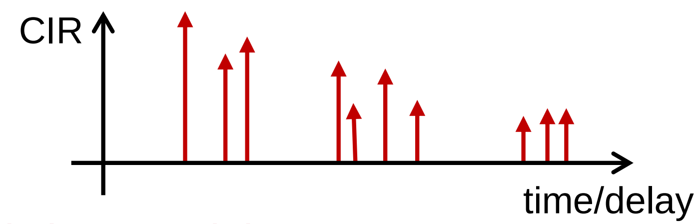
Research Paradigm——Channel Sounding





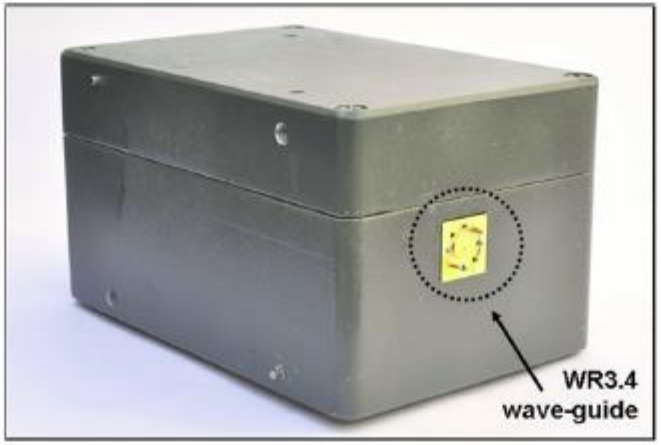
- Channel Sounder
  - Transmits a pseudo random binary sequence (PRBS)
  - Calculates the CIR by cross-correlation of the received signal and the PRBS
- Central Clock Source is necessary for phase recovery

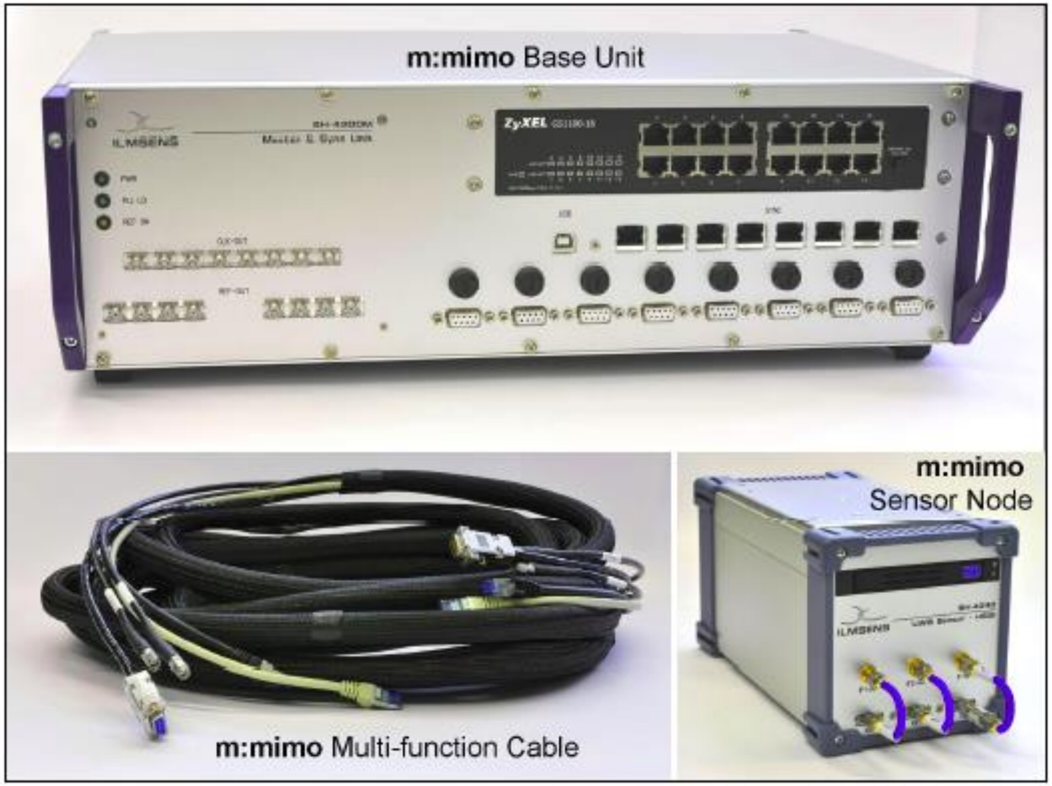
Sebastian Rey, Johannes M. Eckhardt, Bile Peng, **Ke Guan,** and Thomas Kuerner, "Channel sounding techniques for applications in THz communications: A first correlation based channel sounder for ultra-wideband dynamic channel measurements at 300 GHz," *The 9th International Congress on Ultra Modern Telecommunications and Control Systems, ICUMT 2017*, Munich, Germany, November 2017.

Research Paradigm——Channel Sounding

- Three frequency ranges
  - ~9 GHz base IF
  - ~60 GHz frequency extension
  - ~300 GHz frequency extension

- Up to 4x4 MIMO





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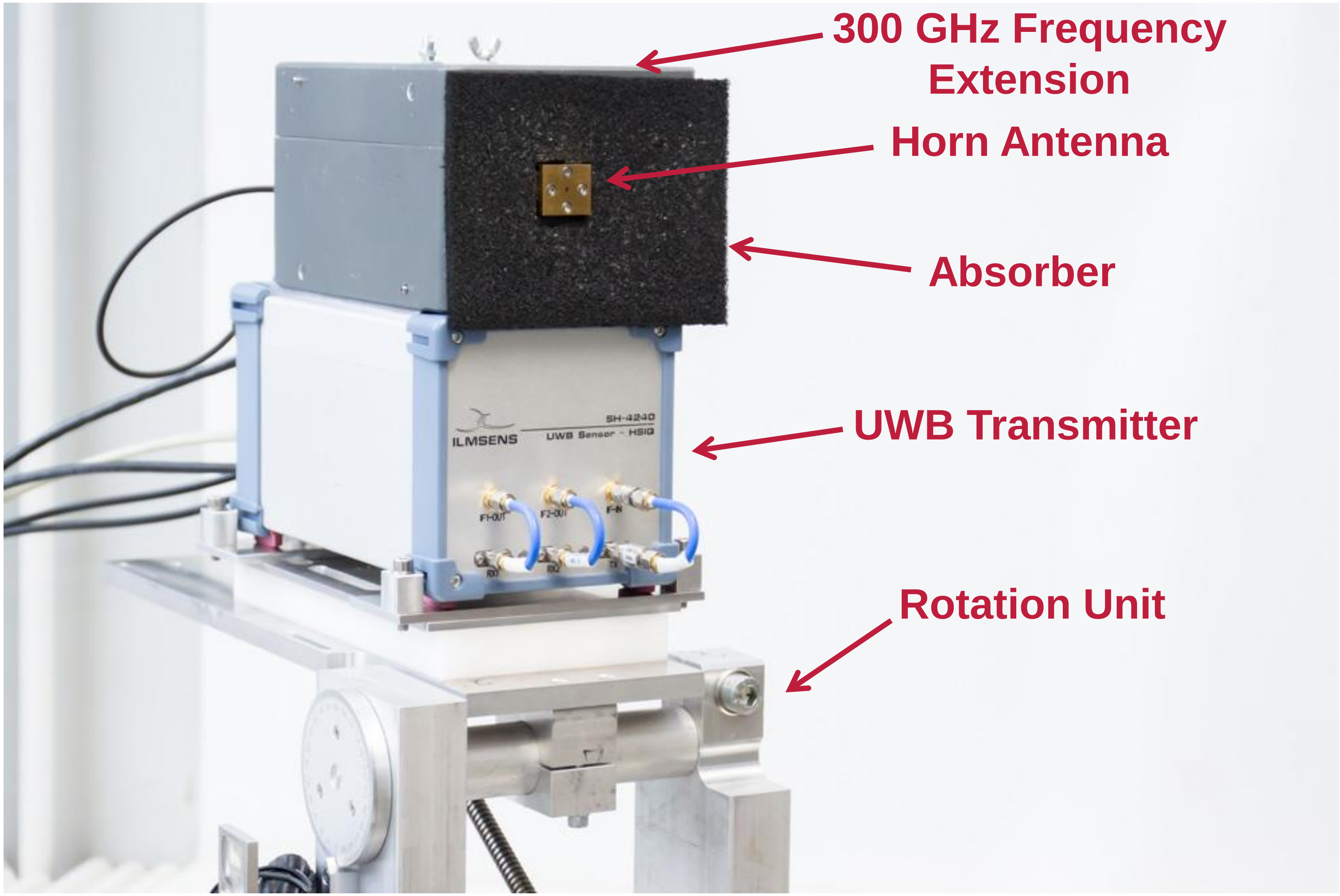
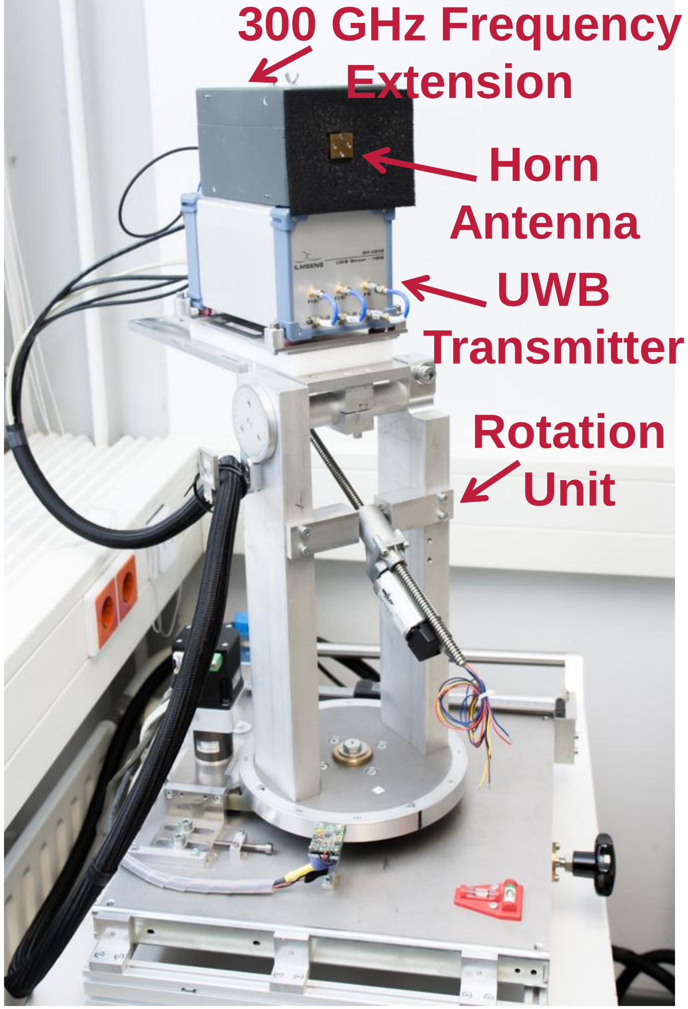
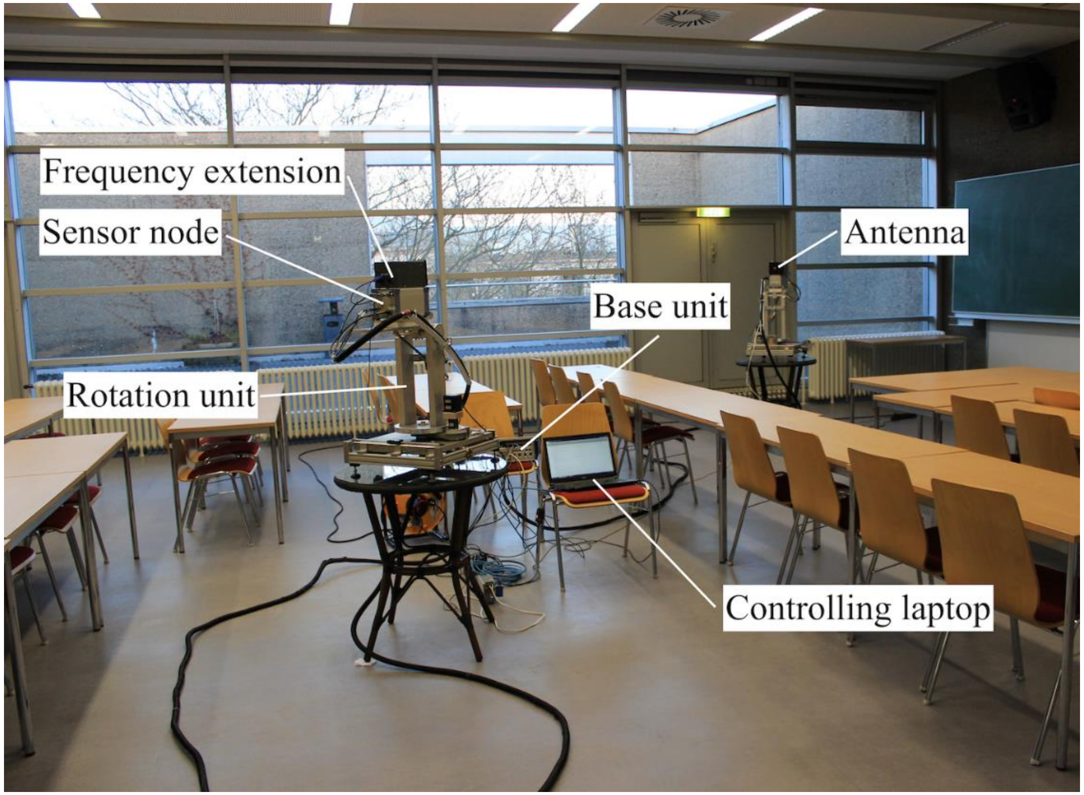
Research Paradigm——Channel Sounding

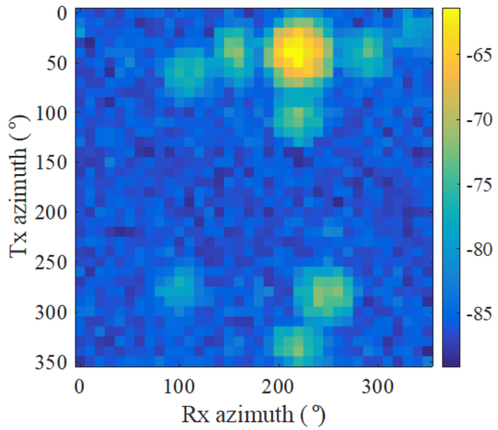


Research Paradigm——Channel Sounding

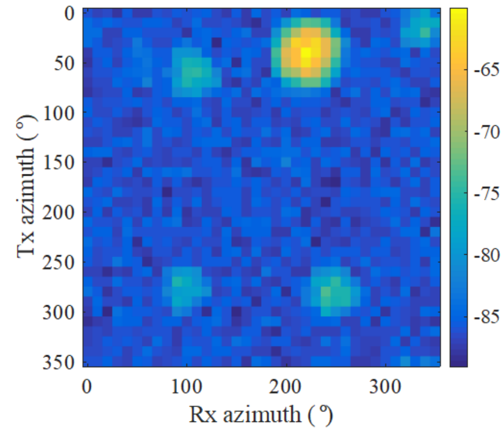




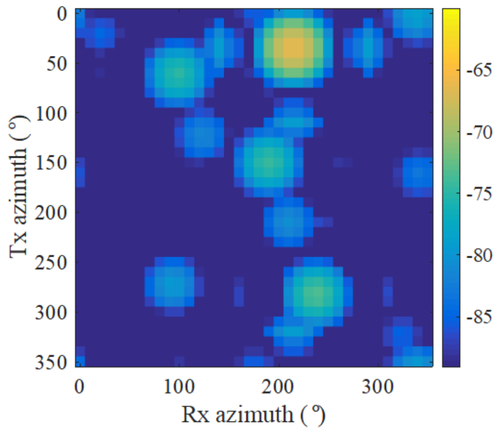
Research Paradigm——Channel Sounding



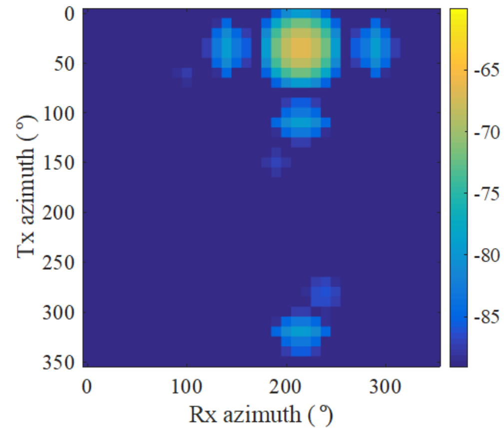
Measured, vertical polarization



Measured, horizontal polarization

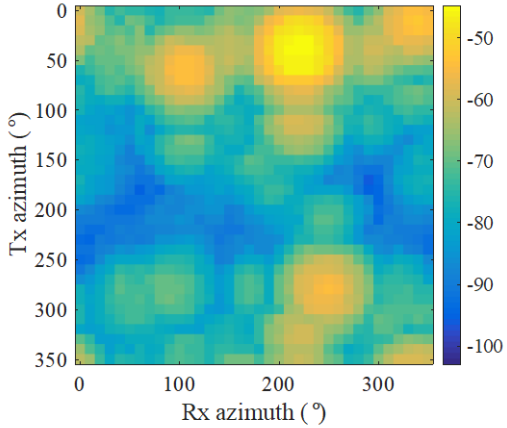


Simulated, vertical polarization

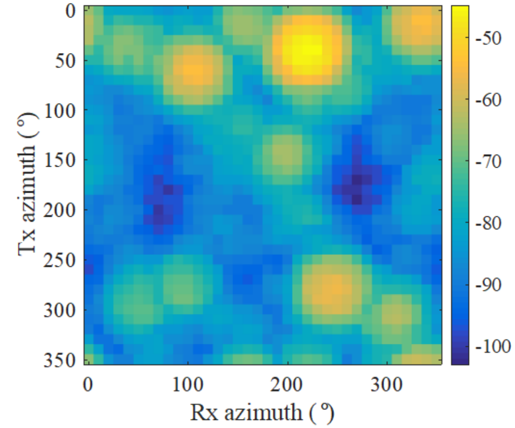


Simulated, horizontal polarization

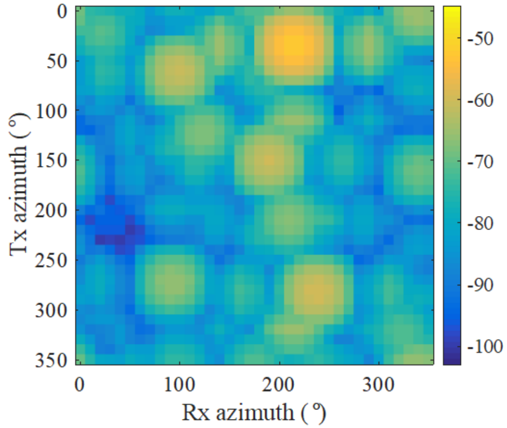
Research Paradigm——Channel Sounding



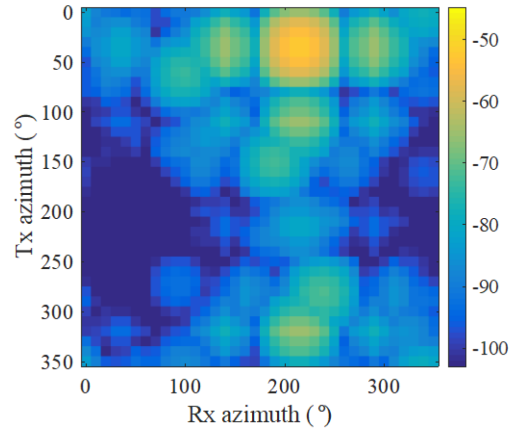
Measured, vertical polarization



Measured, horizontal polarization



Simulated, vertical polarization



Simulated, horizontal polarization

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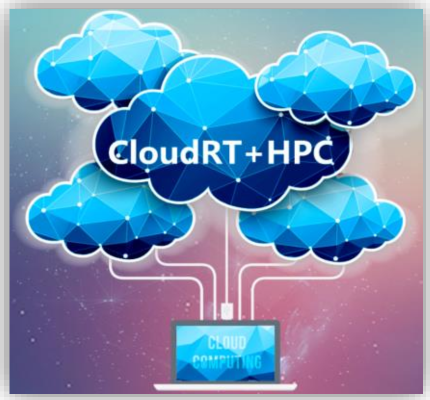
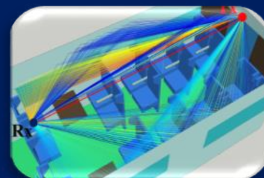
Research Paradigm——Ray Tracing

CloudRT (http://www.raytracer.cloud)

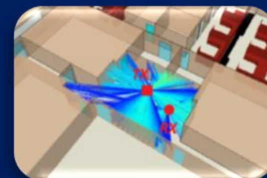


HPC platform: 600 CPU cores, 5 GPUs, and 44 TB storage
Accuracy: validated by 20+ measurements (0.9-300 GHz)

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



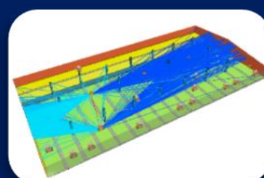
THz enabled 6G



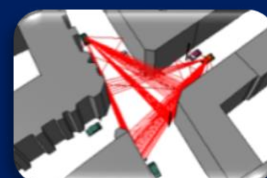
5G

WLAN

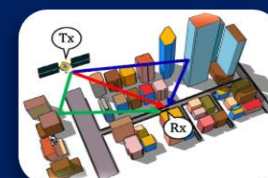
UAV



Industrial IoT



Autonomous driving

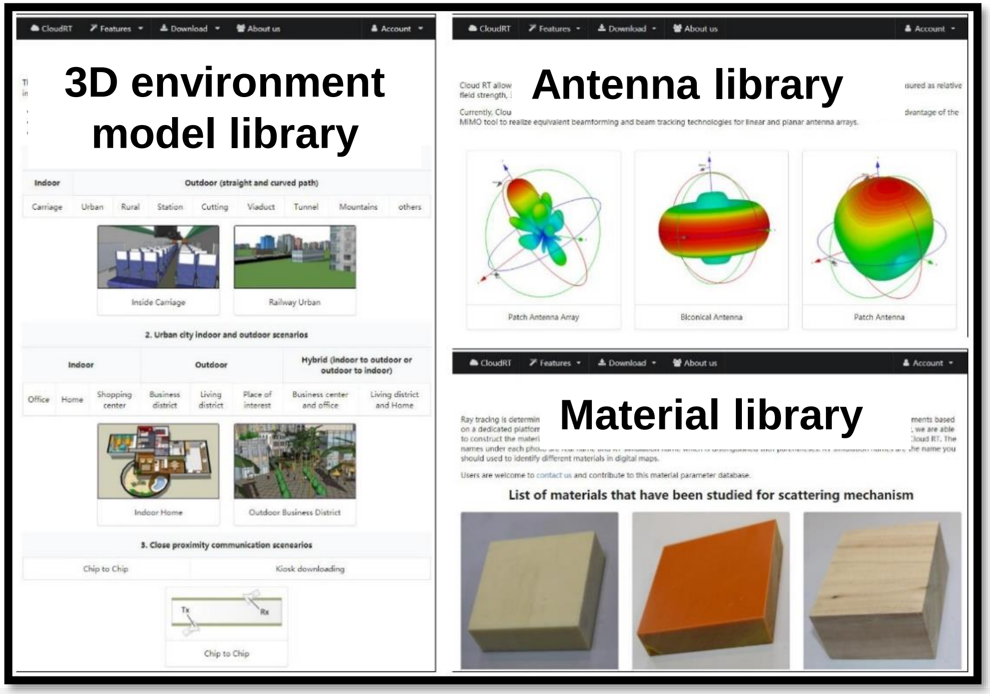


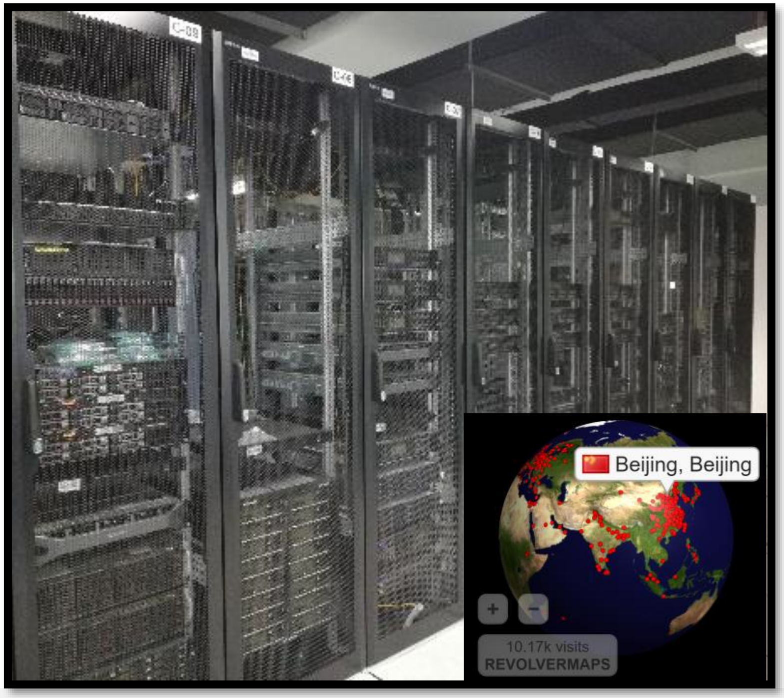
Satellite

Smart railway

Danping He, Bo Ai, **Ke Guan***, Longhe Wang, Zhangdui Zhong, and Thomas 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)**

CloudRT (http://www.raytracer.cloud)





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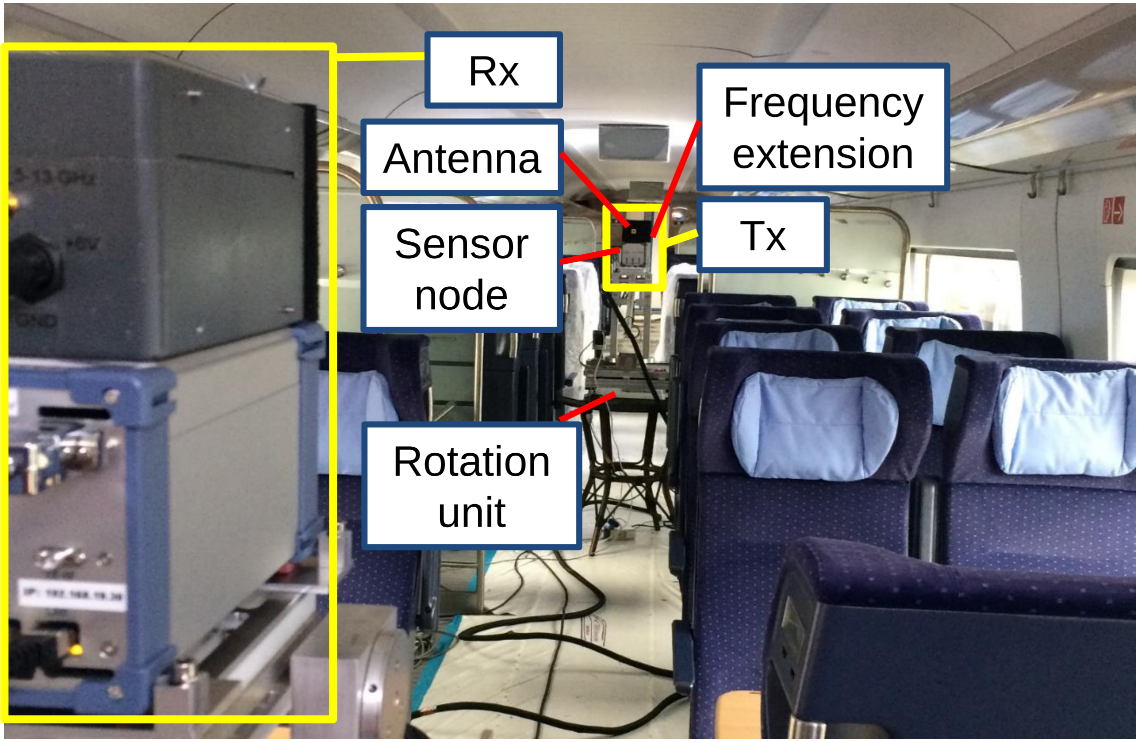
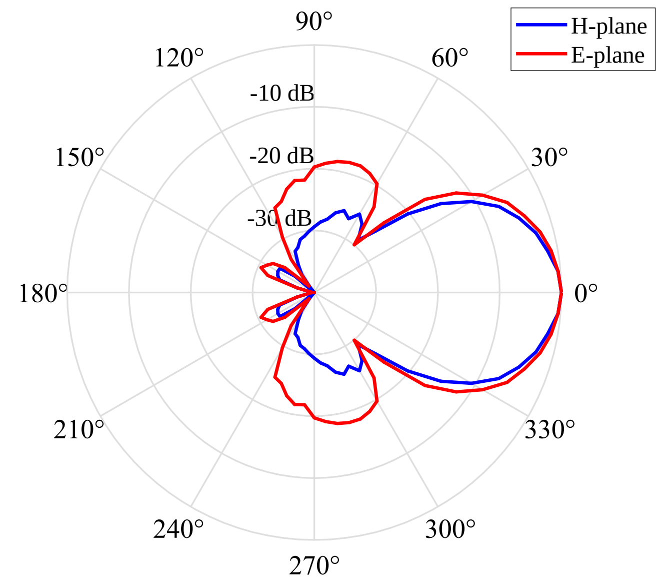
   - Inside Station and T2I Scenarios
   - T2T and I2I Scenarios
   - Panorama of Smart Rail Mobility THz Channel Characteristics
4. Conclusion and Future Work

Intra-wagon Scenario——Channel Sounding



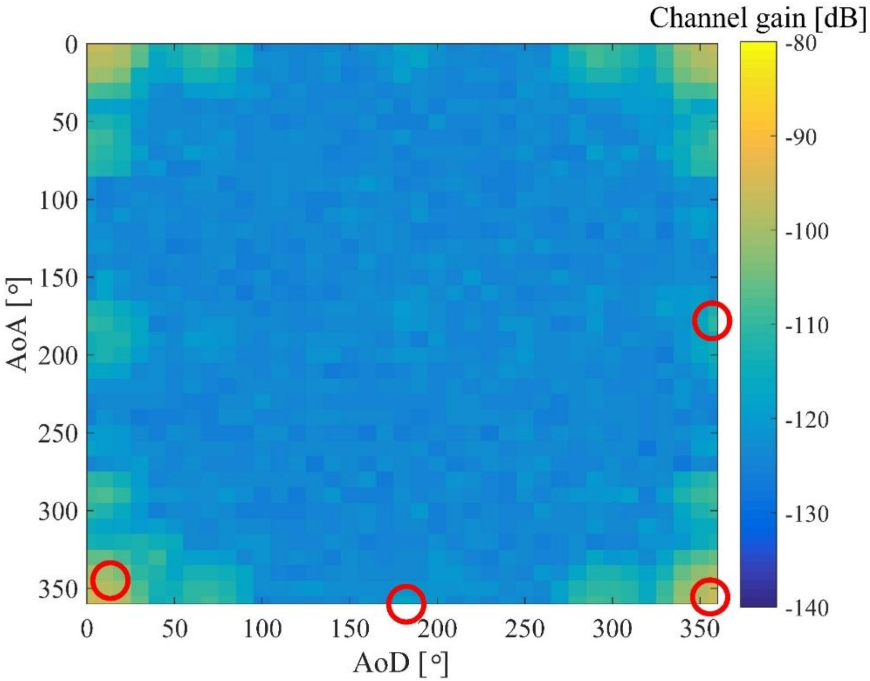
Measurement campaign in a real high-speed train wagon

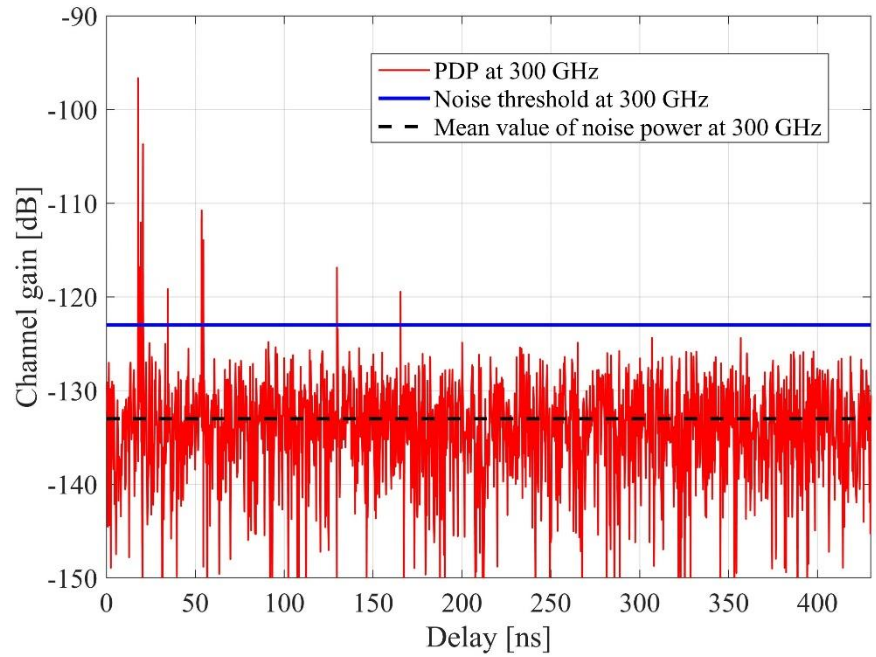


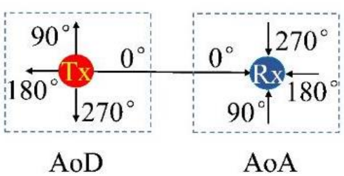
2D pattern of Tx and Rx antennas in the measurement

Measurement system	Bandwidth	Central frequency	Antenna type	Antenna gain	Antenna HPBW	Angular resolution
	8 GHz	304.2 GHz	Directional	15 dBi	30°	10°

Intra-wagon Scenario——Channel Sounding



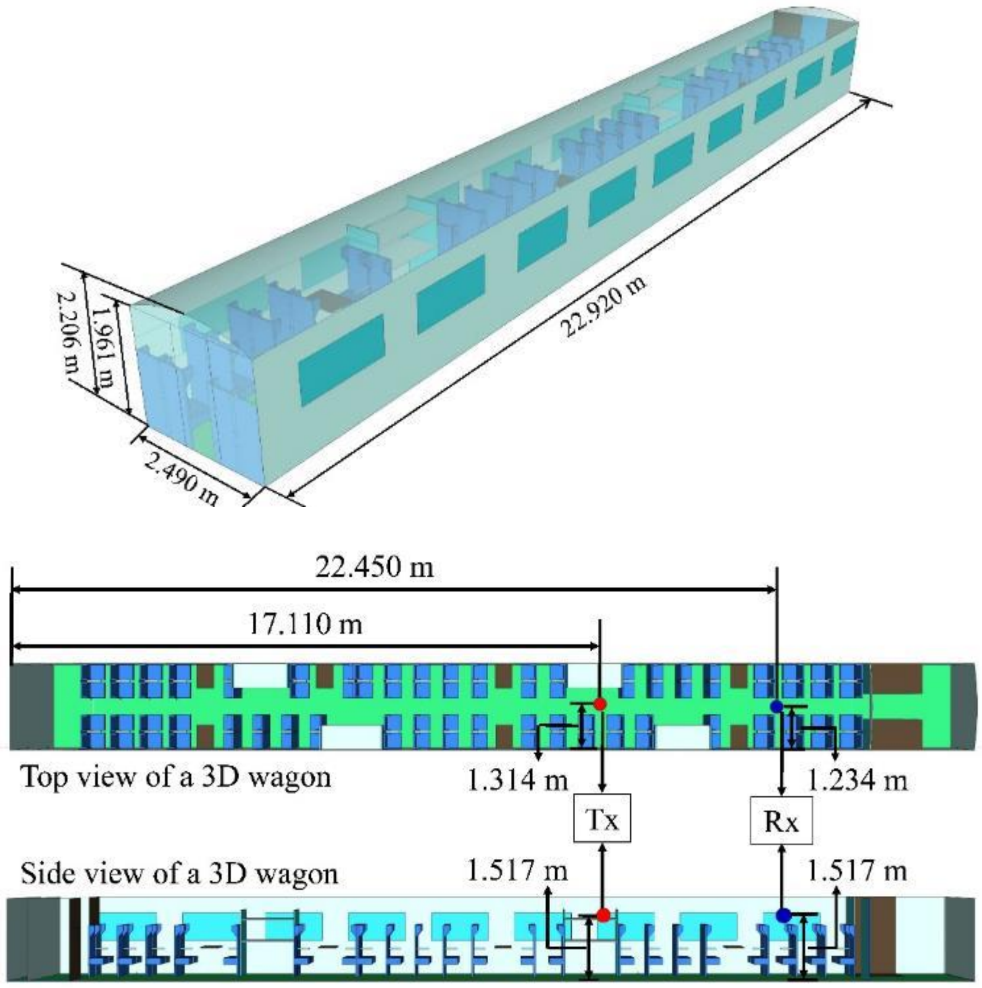




Frequency band	Rician K-factor	RMS DS	ASA	ASD
300 GHz	8.39 dB	11.74 ns	36.68°	18.75°

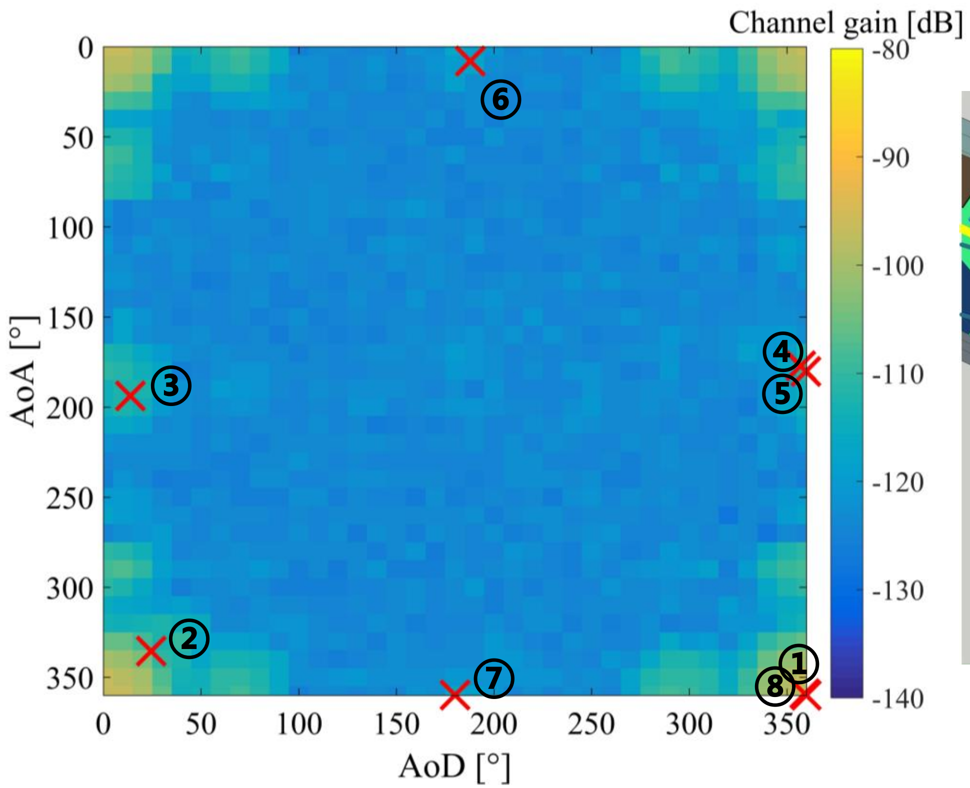
Ke Guan, Bile Peng, Danping He, Johannes M. Eckhardt, Haofan Yi, Sebastian Rey, Bo Ai, Zhangdui Zhong, and Thomas Kuerner, “Channel Sounding and Ray Tracing for Intra-Wagon Scenario at mmWave and sub-mmWave Bands,” ***IEEE Transactions on Antennas and Propagation***, vol. 69, no. 2, pp. 1007-1019, 2021.

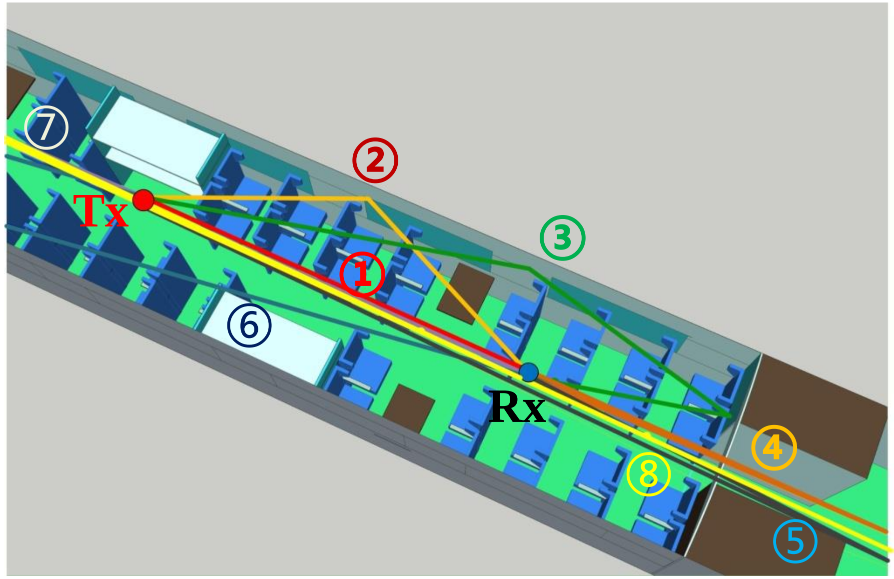
Intra-wagon Scenario——Ray Tracing



Antenna type	**Omni-directive**
Polarization	**Vertical**
Antenna gain	**0 dBi**
Tx power	**0 dBm**
Tx/Rx locations	**Aisle**
Tx/Rx heights	**1.517 m**
Frequency range	**300-308 GHz**
Frequency points	**3200**
Propagation mechanism	**LOS+ 1st order of reflection**

Intra-wagon Scenario——Ray Tracing





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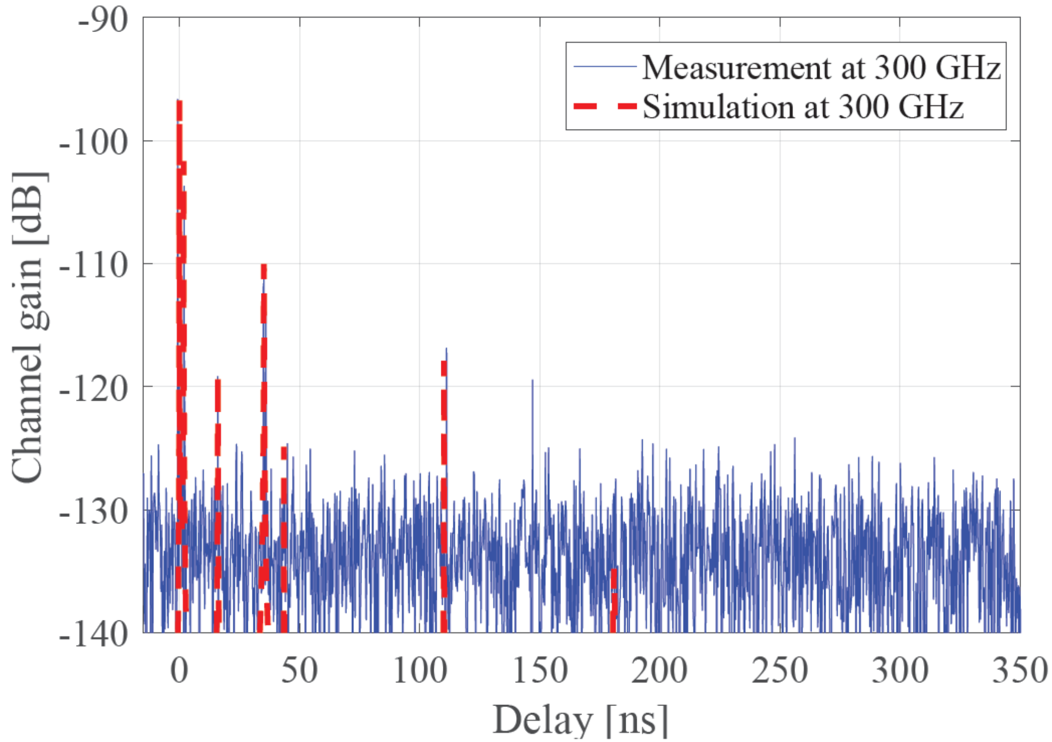
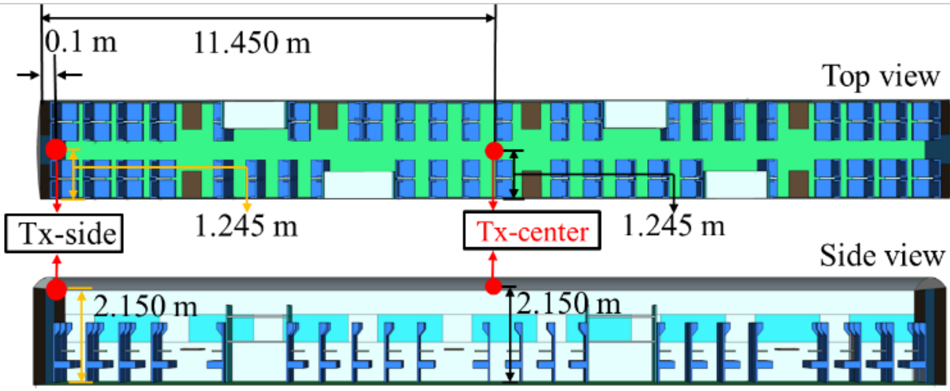
Intra-wagon Scenario——Ray Tracing

Material	ε_r'	ε_r''
Glass	4.200	0.342
Metal	1.000	10^7



Path index	1	2	3	4	5	6	7	8	Mean
Absolute error of gain [dB]	0.00	2.00	0.70	0.57	1.36	0.3	1.00	--	0.85

Intra-wagon Scenario——Extensive Simulations

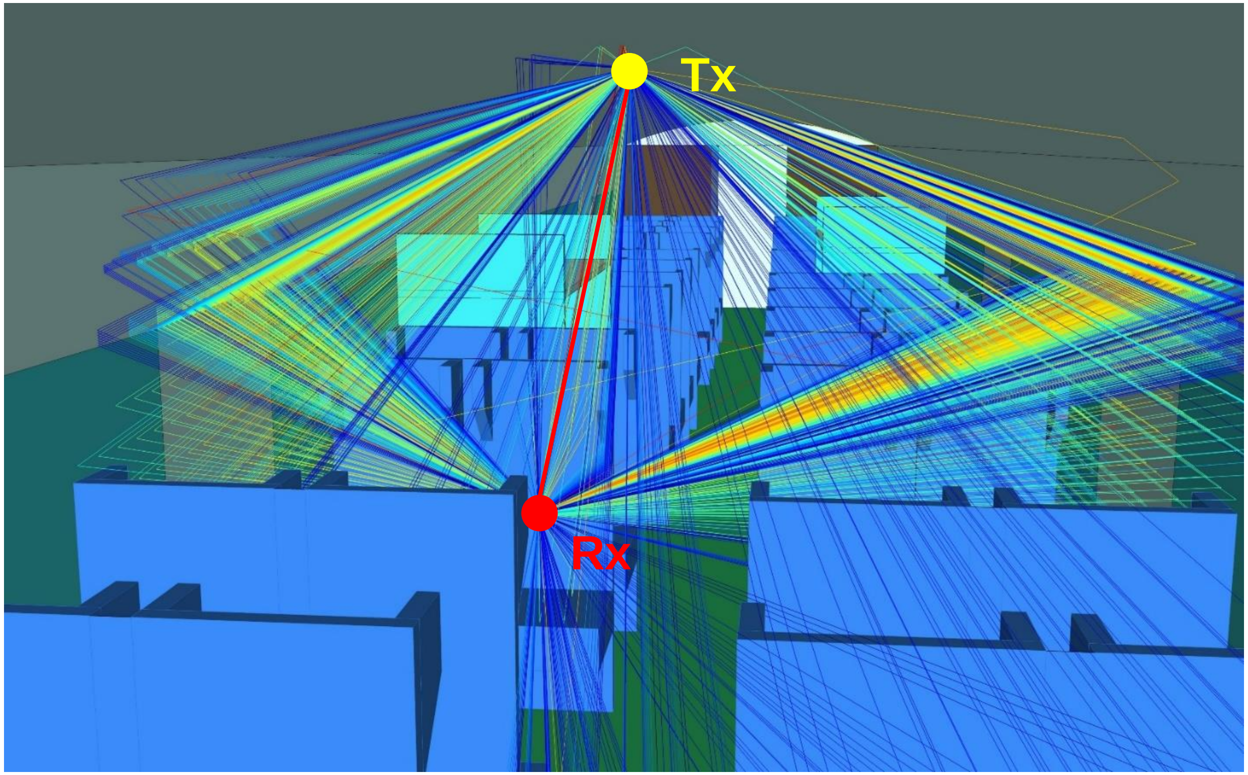


Tx position of the Tx-center deployment and the Tx-side deployment in extensive RT simulations.

EM Property of materials in RT simulation			
Object	Material	ε'	ε''
Wagon body	Metal	1.000	10^7
Windows	Glass	4.200	0.342
Floor	PVC	2.430	0.060
Tables	Wood	1.689	0.070
Chair surface	Nylon	2.989	0.047

Simulation setups for RT validation	
Antenna type	Omni-directive
Polarization	VV, VH, HV, and HH
Antenna gain	0 dBi
Tx power	0 dBm
Tx location	Tx-center, Tx-side
Rx height	0.8 m
Rx spatial separation	0.01 m
Frequency range	300-308 GHz
Frequency points	3200
Propagation mechanism	LOS, reflection up to 1st order, and scattering

Intra-wagon Scenario——Extensive Simulations

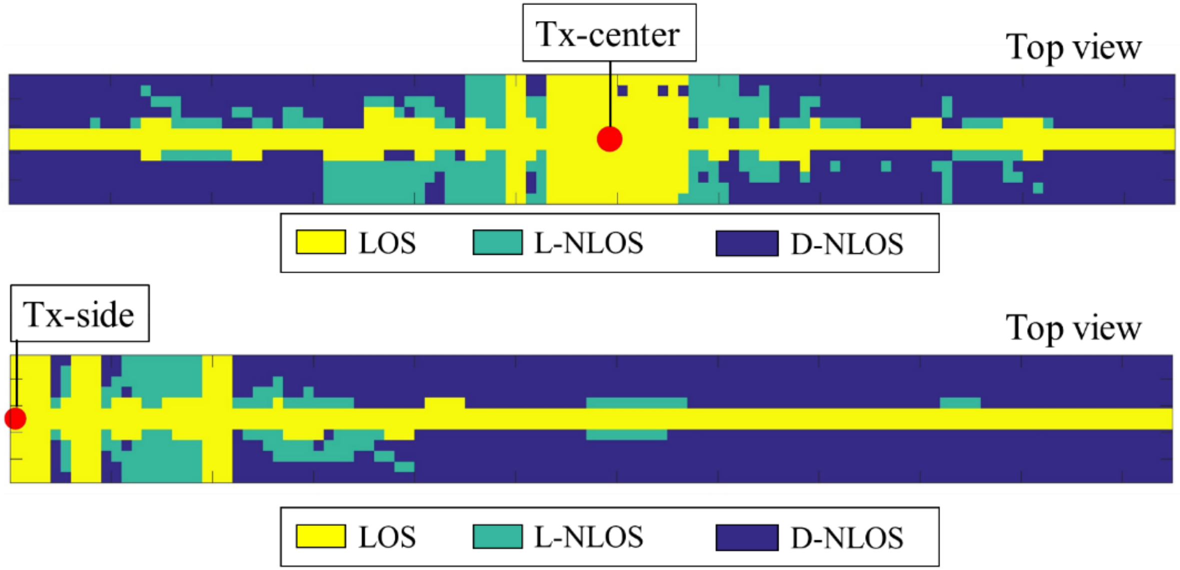


One snapshot of the extensive RT simulations in the high-speed train wagon

Ke Guan, Bile Peng, Danping He, Johannes M. Eckhardt, Haofan Yi, Sebastian Rey, Bo Ai, Zhangdui Zhong, and Thomas Kuerner, "Channel Sounding and Ray Tracing for Intra-Wagon Scenario at mmWave and sub-mmWave Bands," ***IEEE Transactions on Antennas and Propagation***, vol. 69, no. 2, pp. 1007-1019, 2021.

Intra-wagon Scenario——Enhanced Region Classification

Region classified	LOS	1st-order reflection
LOS region	✓	
L-NLOS region	✗	✓
D-NLOS region	✗	✗



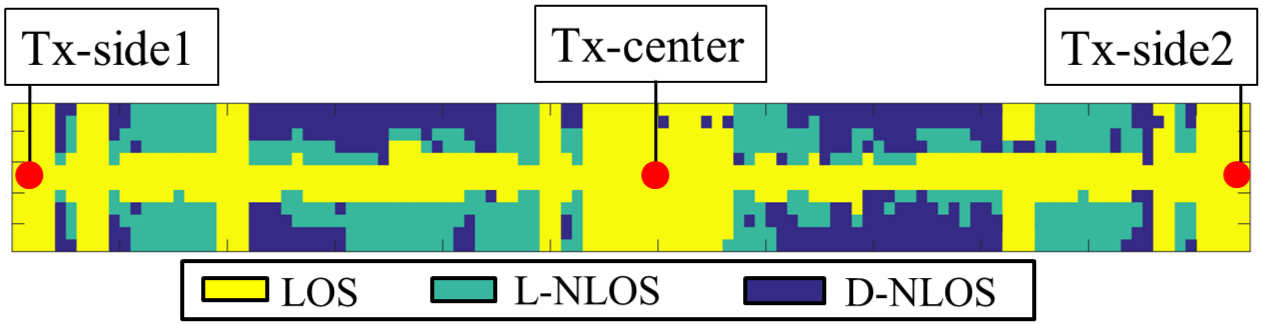
Ke Guan, Bile Peng, Danping He, Johannes M. Eckhardt, Sebastian Rey, Bo Ai, Zhangdui Zhong, and Thomas Kuerner, "Channel Characterization for Intra-Wagon Communication at 60 GHz and 300 GHz Bands," ***IEEE Transactions on Vehicular Technology,*** vol. 68, no. 6, pp. 5193-5207, 2019.

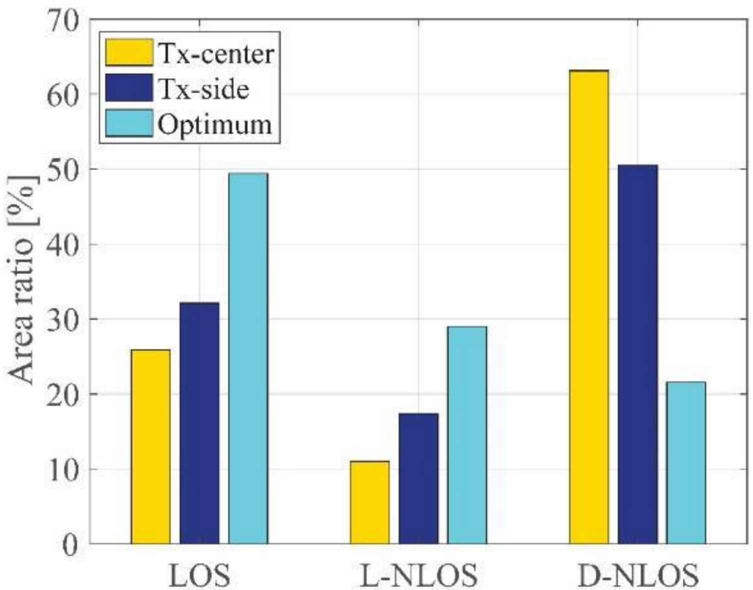
Intra-wagon Scenario——Enhanced Region Classification

Case	Tx-center			Tx- side		
Propagation zone	LOS	L-NLOS	D-NLOS	LOS	L-NLOS	D-NLOS
A	21.66	22.12	9.48	20.68	25.81	35.05
B	79.77	82.16	101.42	79.95	78.96	76.04
σ_{SF} [dB]	5.59	5.54	8.23	5.61	5.14	7.61
μ_{KF} [dB]	6.90	0.06	-13.60	4.27	0.22	-13.57
σ_{kF} [dB]	8.84	5.11	15.35	7.98	5.26	12.18
……						

- **The first-order reflection becomes almost the only chance to build the link if the LOS is blocked.**
- **The RT simulation results imply that the existence of the first-order reflection indeed determines the channel characteristics.**

Intra-wagon Scenario——Optimum Tx Deployment





Area ratios	Tx-center	Tx-side	Optimum
LOS	25.9%	32.1%	49.4%
L-NLOS	11.0%	17.4%	29.0%
D-NLOS	63.1%	50.5%	21.6%

Ke Guan, Bile Peng, Danping He, Johannes M. Eckhardt, Sebastian Rey, Bo Ai, Zhangdui Zhong, and Thomas Kuerner, "Channel Characterization for Intra-Wagon Communication at 60 GHz and 300 GHz Bands," ***IEEE Transactions on Vehicular Technology***, vol. 68, no. 6, pp. 5193-5207, 2019.

Intra-wagon Scenario——Channel Characterization

Frequency	300 GHz band					
Tx deployment	Tx-center			Tx-side		
Propagation zone	LOS	L-NLOS	D-NLOS	LOS	L-NLOS	D-NLOS
A	21.66	22.12	9.48	20.68	25.81	34.05
B	79.77	82.16	101.42	79.95	78.96	76.04
σ_{SF} [dB]	5.59	5.54	8.23	5.61	5.14	7.61
λ_{SF} [m]	0.03	0.02	0.02	0.04	0.02	0.02
μ_{KF} [dB]	6.90	0.06	-13.60	4.27	0.22	-13.57
σ_{KF} [dB]	8.84	5.11	15.35	7.98	5.26	12.18
λ_{KF} [m]	0.25	0.25	0.11	0.24	0.25	0.15
μ_{DS} [$\log_{10}$([s])]	-8.59	-8.81	-8.94	-8.71	-8.73	-8.88
σ_{DS} [$\log_{10}$([s])]	0.36	0.27	0.35	0.42	0.24	0.68
λ_{DS} [m]	0.24	0.25	0.15	0.18	0.23	0.16
r_{DS}	4.02	1.38	1.40	7.46	1.15	1.88
μ_{ASD} [$\log_{10}$([°])]	1.15	1.35	0.33	1.14	1.19	0.97
σ_{ASD} [$\log_{10}$([°])]	0.56	0.53	0.88	0.30	0.50	0.81
λ_{ASD} [m]	0.25	0.26	0.14	0.25	0.25	0.22
μ_{ESD} [$\log_{10}$([°])]	1.37	0.38	-0.05	1.18	0.55	0.59
σ_{ESD} [$\log_{10}$([°])]	0.31	0.25	0.43	0.35	0.45	0.64
λ_{ESD} [m]	0.25	0.25	0.14	0.25	0.25	0.25

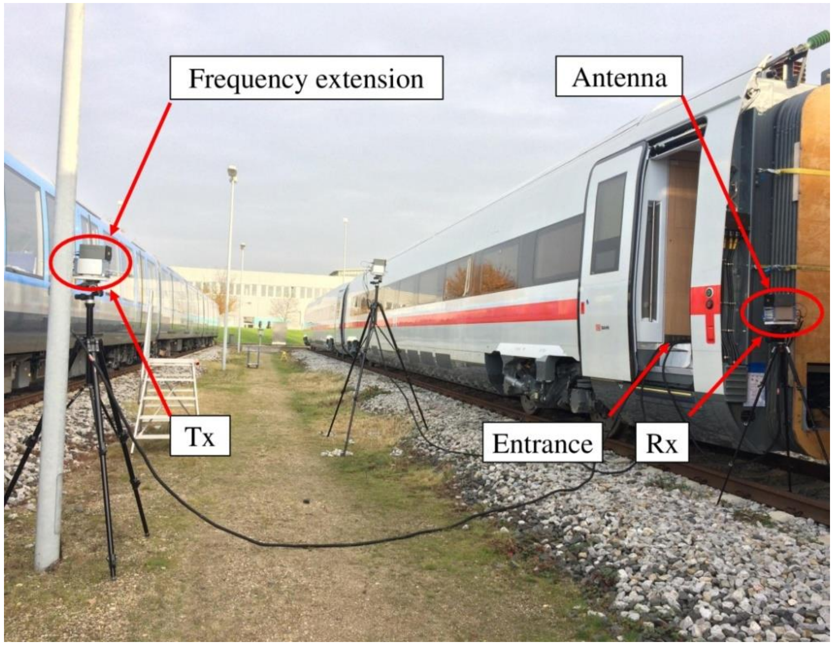
Frequency	300 GHz band					
Tx deployment	Tx-center			Tx-side		
Propagation zone	LOS	L-NLOS	D-NLOS	LOS	L-NLOS	D-NLOS
μ_{ASA} [$\log_{10}$([°])]	1.30	1.8	1.38	1.24	1.73	1.67
σ_{ASA} [$\log_{10}$([°])]	0.67	0.30	0.54	0.70	0.34	0.37
λ_{ASA} [m]	0.25	0.25	0.10	0.26	0.25	0.18
μ_{ESA} [$\log_{10}$([°])]	0.62	0.97	0.78	0.52	0.90	1.00
σ_{ESA} [$\log_{10}$([°])]	0.52	0.33	0.56	0.61	0.26	0.35
λ_{ESA} [m]	0.25	0.25	0.18	0.25	0.25	0.16
μ_{XPR} [dB]	21.91	2.05	-0.06	12.99	2.62	1.92
σ_{XPR} [dB]	5.16	2.62	1.91	4.83	2.99	2.98
NumCluster	3	5	5	3	5	5
PCParameter						
SF [dB]	12.71	11.67	32.74	10.35	13.89	12.64
ASD [°]	12.30	6.82	3.44	17.03	2.76	1.75
ESD [°]	3.52	1.29	0.54	4.18	2.00	1.72
ASA [°]	16.59	7.23	5.78	24.64	8.14	7.33
ESA [°]	4.98	2.62	3.36	2.86	4.22	4.93

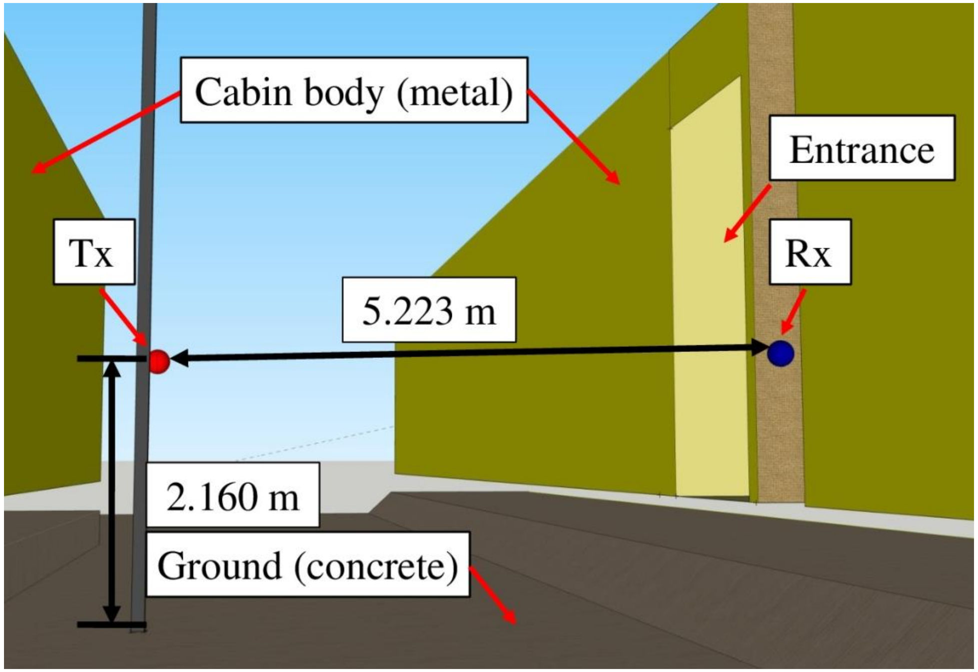
Stochastic Channel Generators, such as 3GPP, Quadriga, etc

Outline

1. Motivation of Smart Rail Mobility enabled by THz
2. Challenge and New Paradigm for THz Mobile Channel Modeling
   - Channel Sounding
   - Ray Tracing
3. **THz Channel Characterization for**
   - Intra-wagon Scenario
   - **Inside Station**
4. Conclusion and Future Work

Inside Station and T2I Scenarios——Channel Sounding





Frequency band	Antenna type
300.2-308.2 GHz	Directional

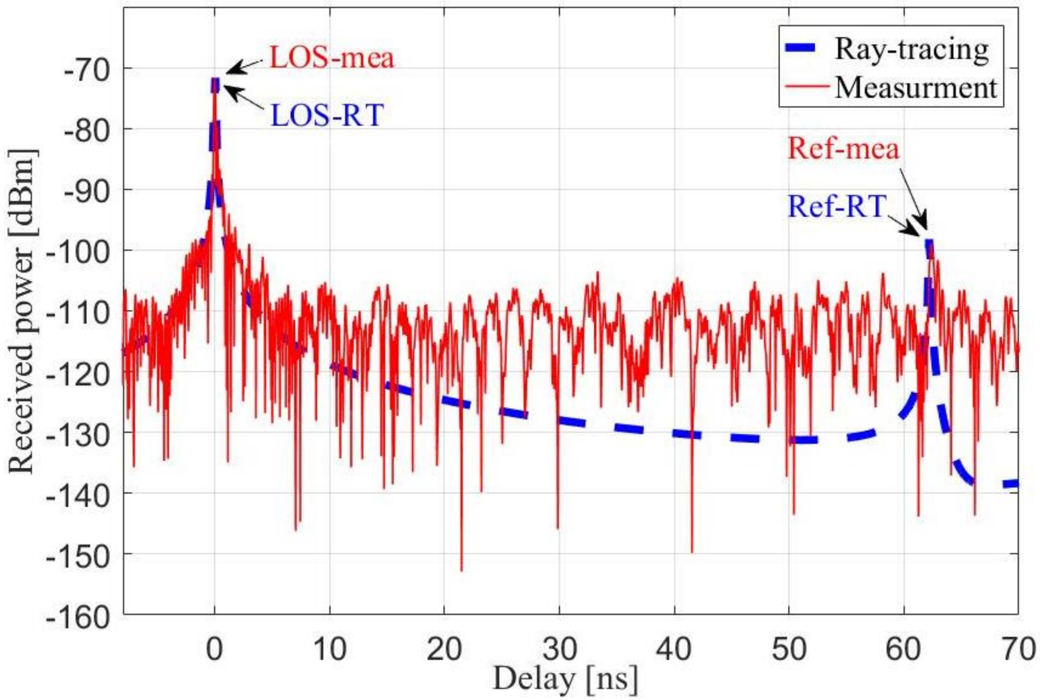
Frequency band	Rician K-factor	RMS DS
300 GHz	**3.52 dB**	**8.92 ns**

Ke Guan, Bile Peng, Danping He, et al., "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.

Inside Station and T2I Scenarios——Ray Tracing

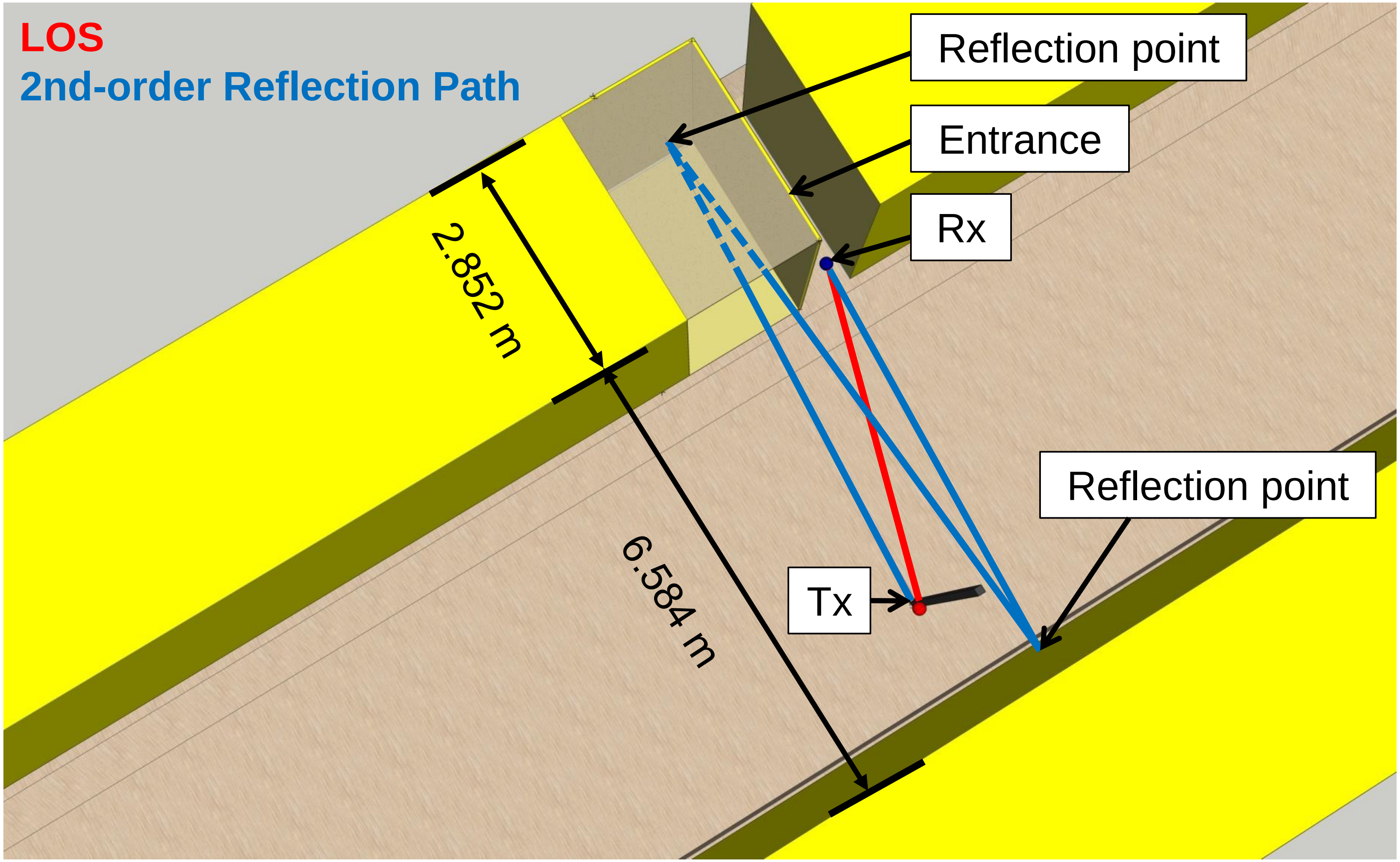
Path (Measurement)	LOS - mea	Ref- mea
Received power [dBm]	-71.66	-98.95
Delay [ns]	0.00	62.36

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

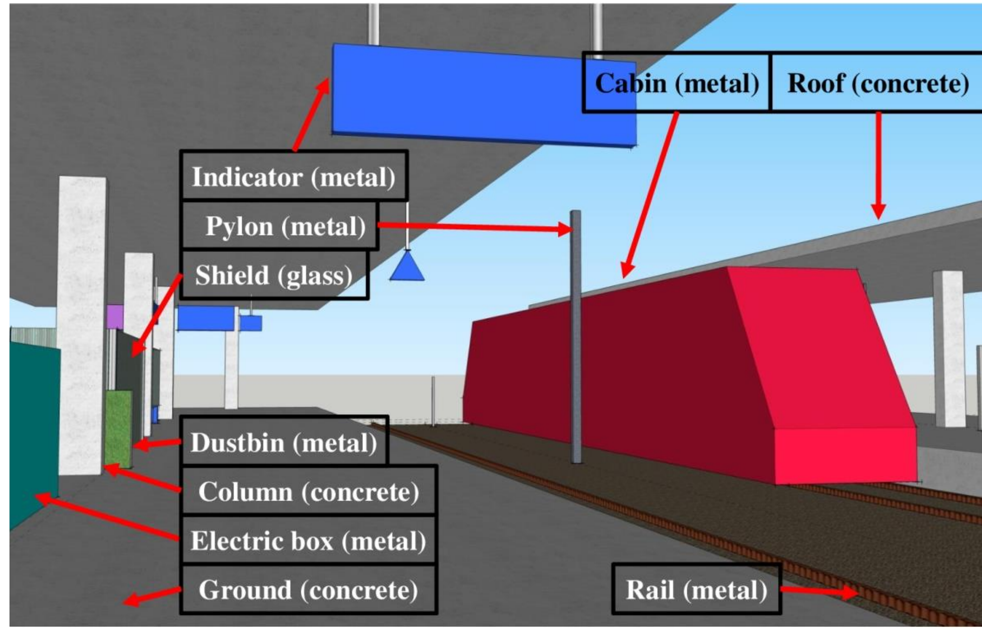


Validated reflection order
2

T2I and Inside Station Scenario——Propagation Mechanism

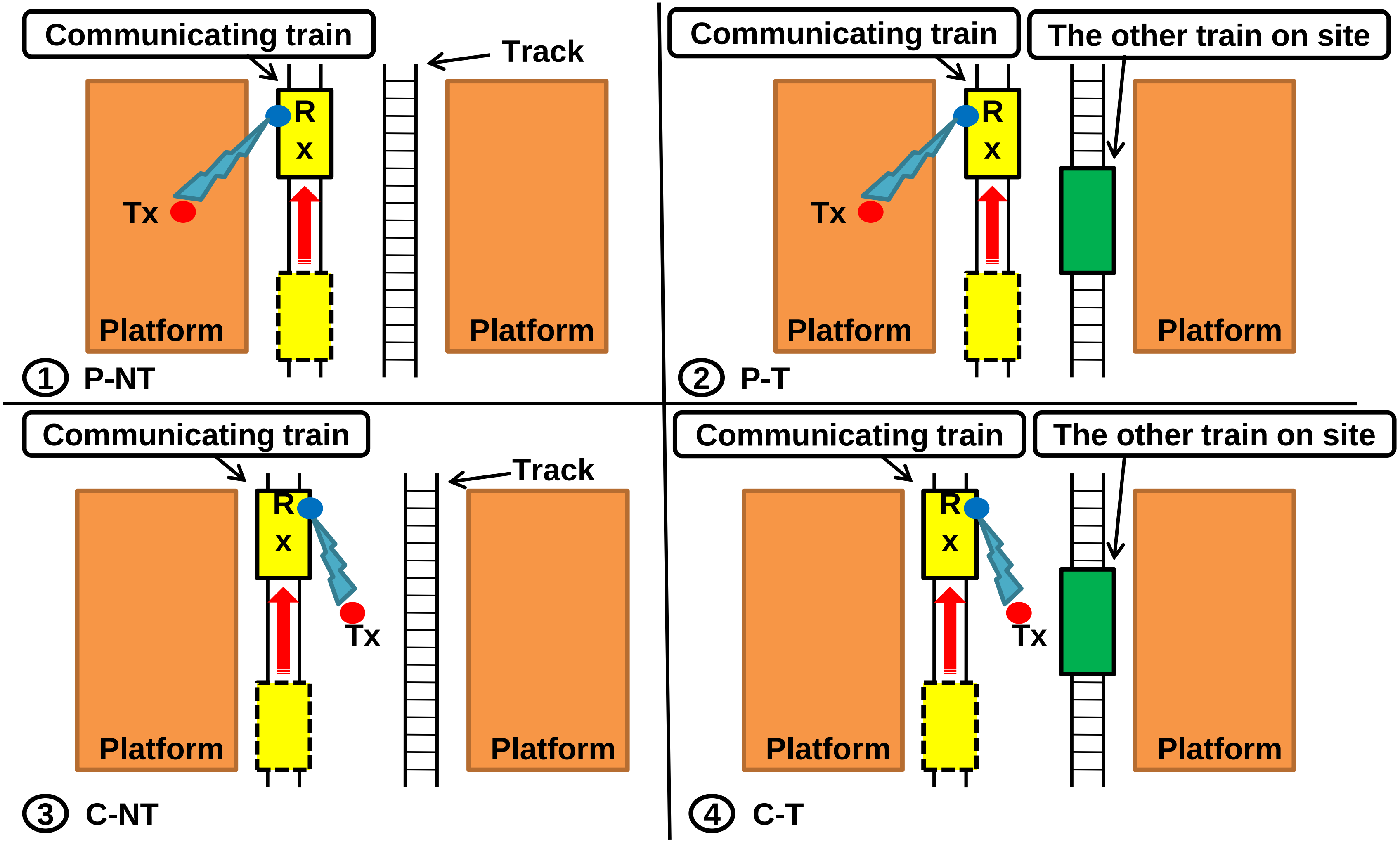


Inside Station Scenario——Extensive Simulations

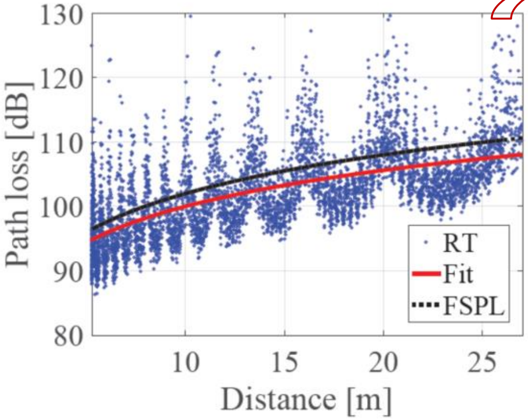


Polarization	**VV, VH, HH, and HV**
Antenna type	**Isotropic**
Antenna gain and Tx power	**0 dBi and 0 dBm**
Frequency range	**300-308 GHz**
Propagation mechanism	**LOS + 2nd order of reflection + scattering**

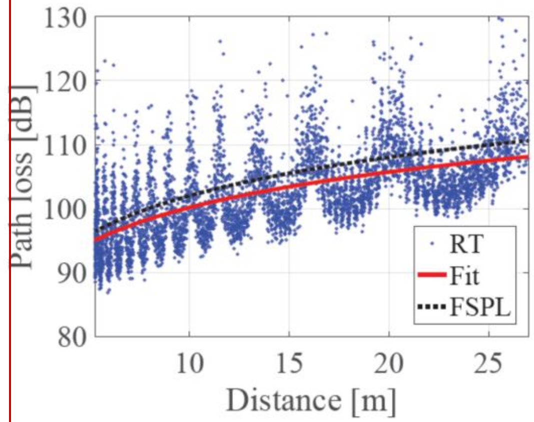
Inside Station Scenario——Four Cases



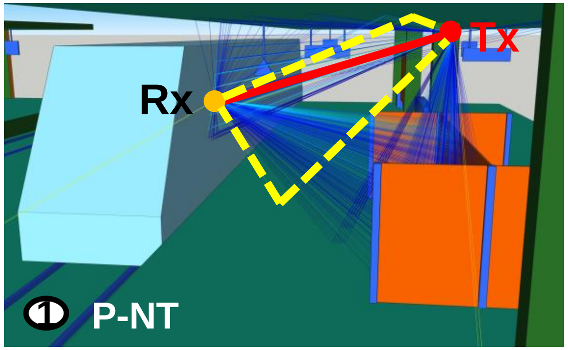
Inside Station Scenario——Channel Characterization

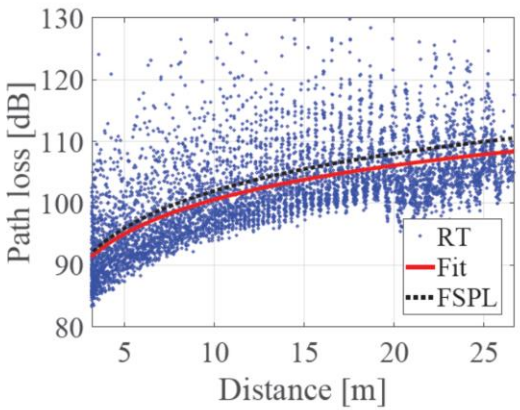


(a) P-NT case

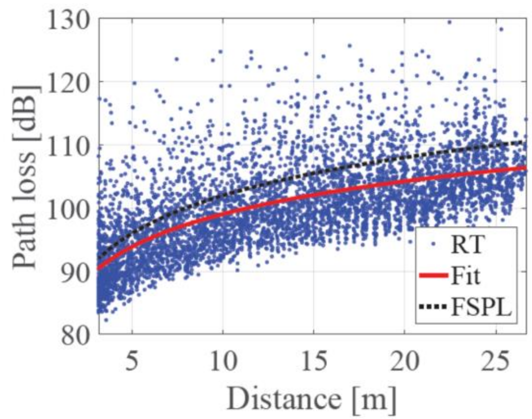


(b) P-T case

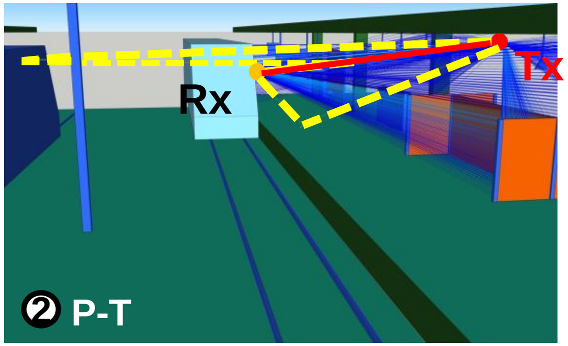




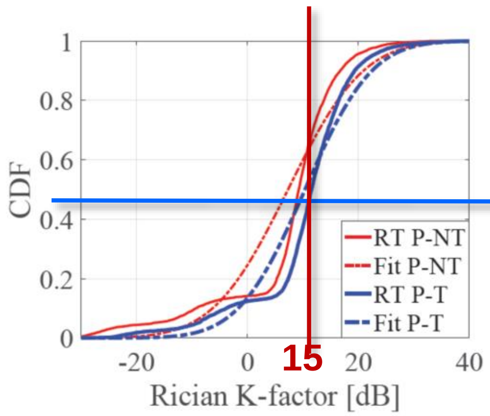
(c) C-NT case



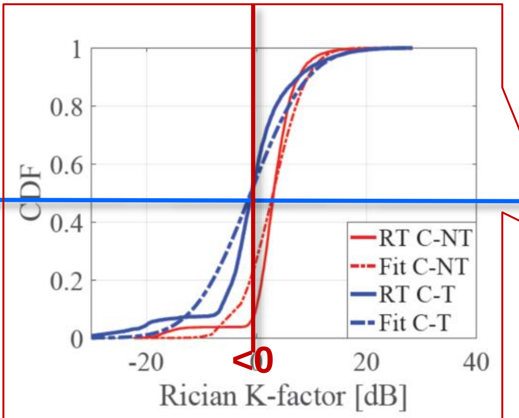
(d) C-T case



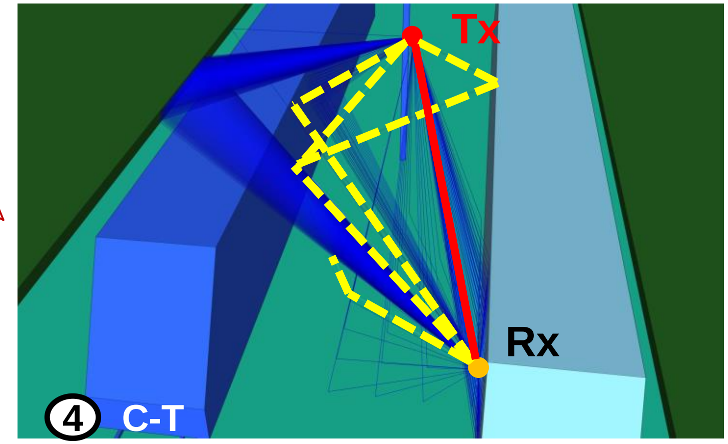
Inside Station Scenario——Channel Characterization

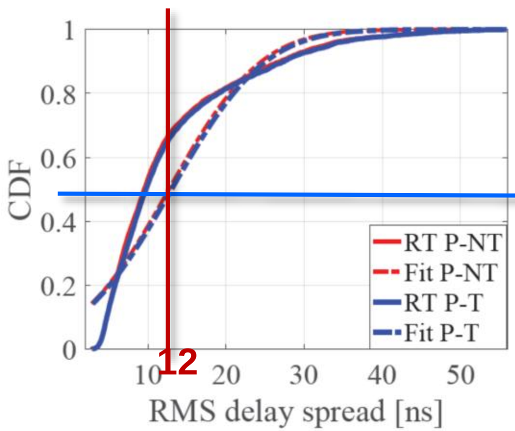


(a) P-NT and P-T cases

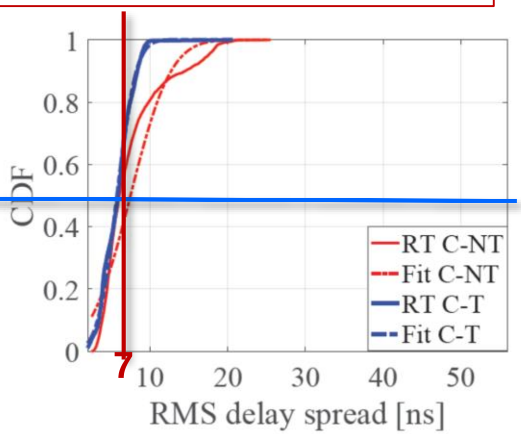


(b) C-NT and C-T cases





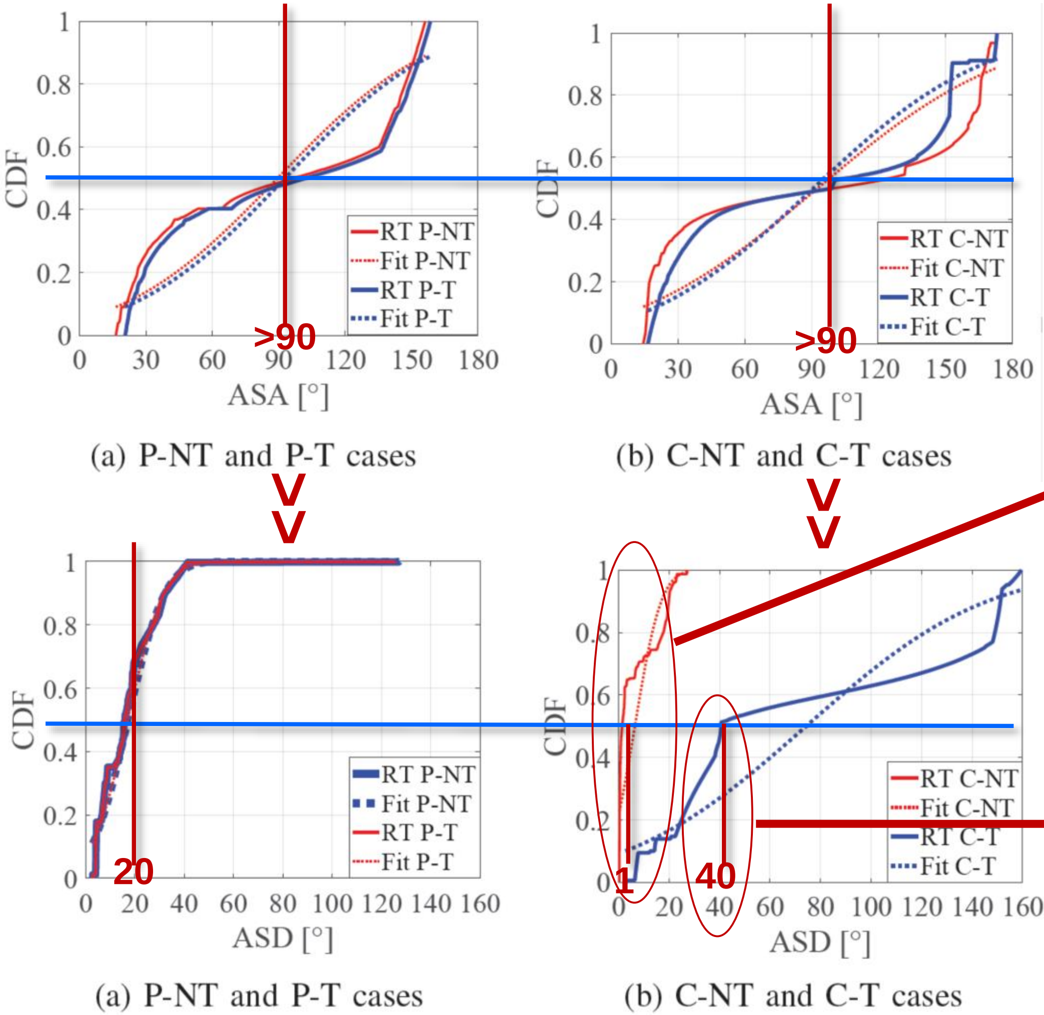
(a) P-NT and P-T cases

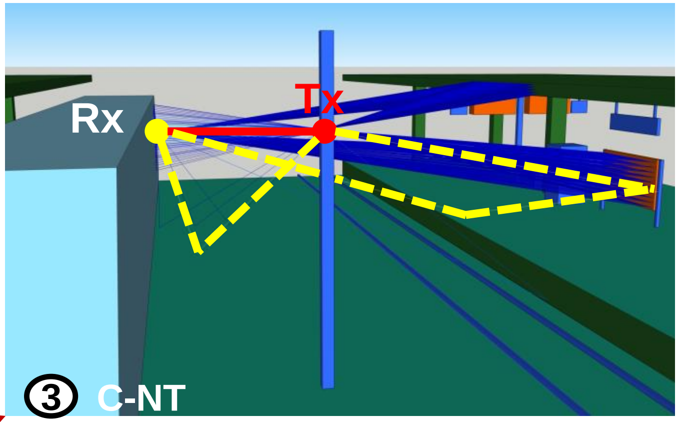


(b) C-NT and C-T cases

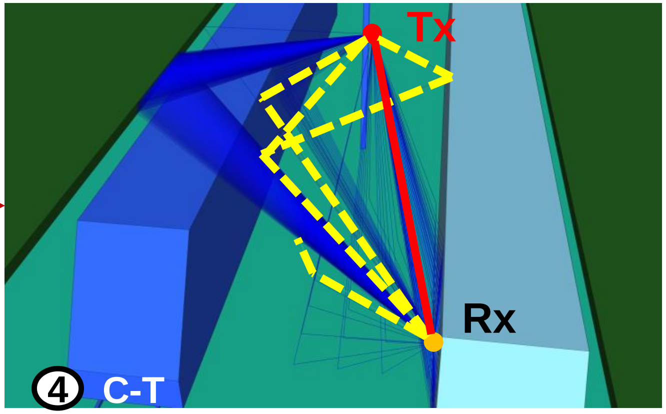
- Much **stronger multipaths** can be received when the **Tx** is deployed on the **catenary mast**.
- The **reflection attenuation** caused by **metallic** train body is **trivial**, and therefore, considerably decrease the KF.

Inside Station Scenario——Channel Characterization

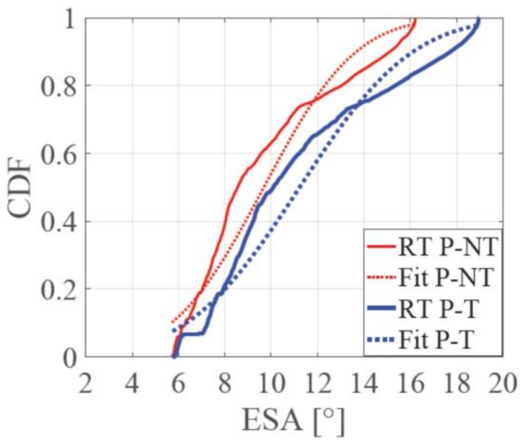




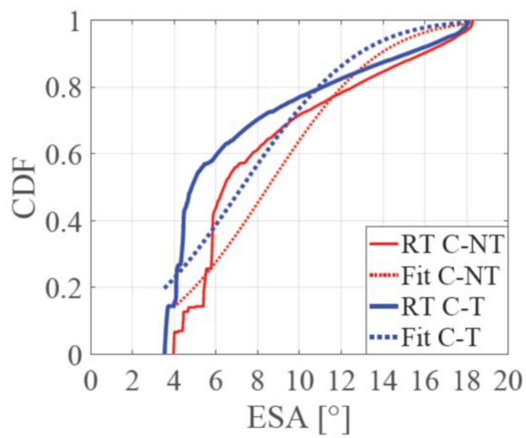
The **other train** generates **strong multipaths** to **increase** the **ASD**.



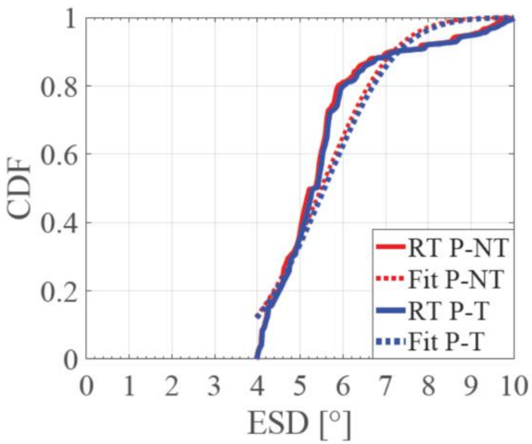
Inside Station Scenario——Channel Characterization



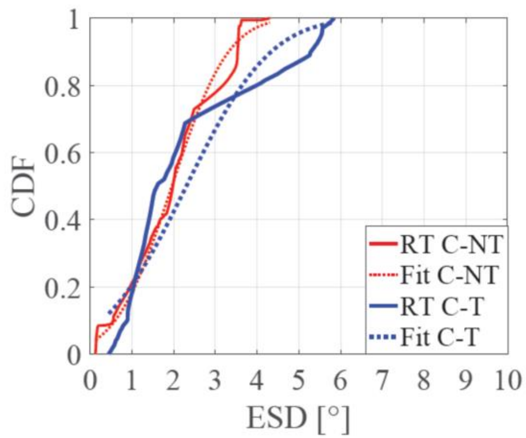
(a) P-NT and P-T cases



(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.

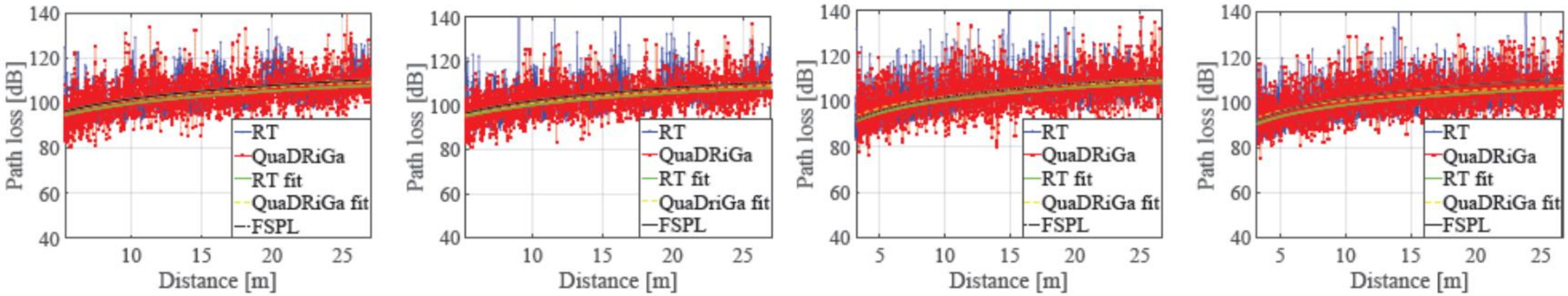
Inside Station Scenario——Channel Characterization

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

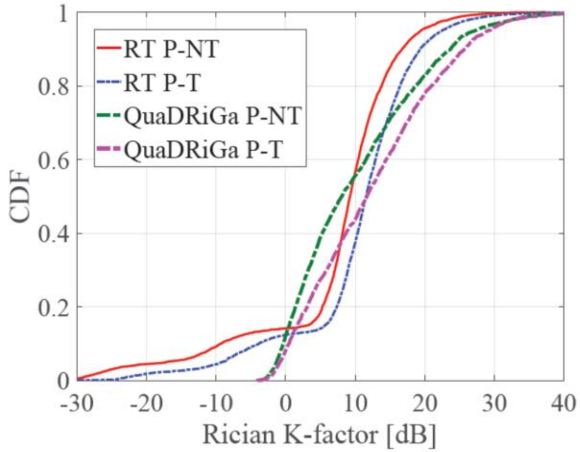
Channel Case	T2I inside station P-NT	P-T	C-NT	C-T
μ_{ASD} $[\log_{10}([^\circ])]$	1.12	1.13	0.33	1.70
σ_{ASD} $[\log_{10}([^\circ])]$	0.32	0.32	0.69	0.43
λ_{ASD} [m]	0.25	0.25	0.25	0.25
μ_{ESD} $[\log_{10}([^\circ])]$	0.73	0.74	0.18	0.27
σ_{ESD} $[\log_{10}([^\circ])]$	0.09	0.09	0.38	0.29
λ_{ESD} [m]	0.25	0.25	0.25	0.25
μ_{ASA} $[\log_{10}([^\circ])]$	1.83	1.86	1.79	1.82
σ_{ASA} $[\log_{10}([^\circ])]$	0.35	0.32	0.43	0.37
λ_{ASA} [m]	0.25	0.25	0.25	0.25
μ_{ESA} $[\log_{10}([^\circ])]$	0.96	1.02	0.88	0.80
σ_{ESA} $[\log_{10}([^\circ])]$	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

Inside Station Scenario——Channel Characterization

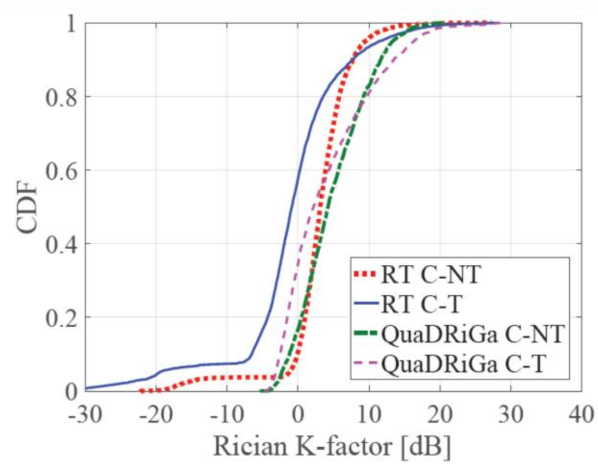


(a) P-NT case of T2I (b) P-T case of T2I (c) C-NT case of T2I (d) C-T case of T2I

Path loss and shadow fading for Inside station channel (QuaDRiGa vs RT)



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



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

Conclusion and Future Work

- **New paradigm** of channel modeling: limited channel sounding → calibrated **ray tracing** → extensive simulations → stochastic channel modeling/realization
- **THz propagation features** of **smart rail mobility**:
  - It is sufficient to consider up to the **2nd order of reflection** for propagation mechanism constitution in **Intra-wagon and Inside station** scenarios.
  - Even without the LOS condition, the THz link can be built if **the first order of reflection** exists in the **Intra-wagon** scenario.
  - For the **significant objects**, **train wagons**, **glass window**, and any **metallic objects** with **smooth surface** and **dimensions obviously larger** than the **wavelength of THz wave** should be considered in the 3D model reconstruction.
  - For the **system design**, there are some special concerns, for instance,
    - In **Intra-wagon** scenario, there may be **multipaths** with the **same delay** but **very different directions**.
    - The **inner wall** of wagon (when door open) can **reflect multipaths** with unexpected **long delay** in the **Inside station** scenario;

Thank you for your attention.

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