NIST mmWave Channel Propagation Measurements and Modeling

National Institute of Standards and Technology
U.S. Department of Commerce

Communications Technology Laboratory

Contributors

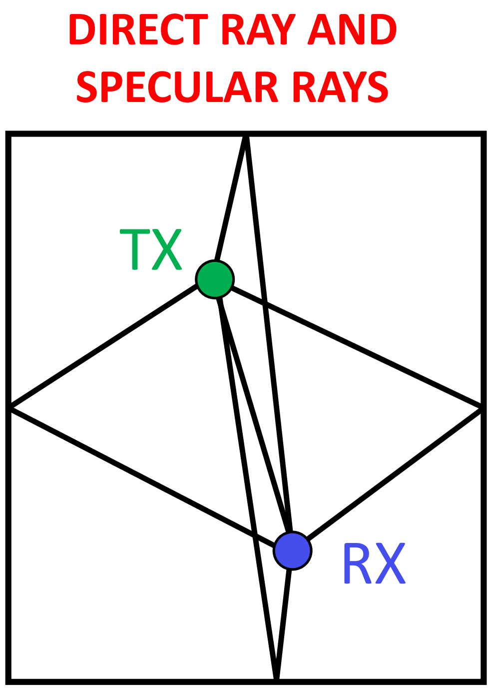
- A. Agrahari (G)
- A. Bodi (G)
- D. Caudill (B)
- J. Chuang (G)
- C. Gentile (G)
- N. Golmie (G)
- A. Hughes (G)
- B. Jamroz (B)
- S.-Y. Jun (B)
- M. Kim (G)
- Y. Kim (G)
- C. Lai (G)
- R. Leonhardt (B)
- J. Quimby (B)
- P. Papazian (B)
- K. Remley (B)
- J. Rezac (B)
- T. Ropitault (G)
- P. Vouras (G)
- N. Varshney (G)
- J. Wang (G)
- A. Weiss (B)
- D. Williams (B)
- J. Zhang (G)

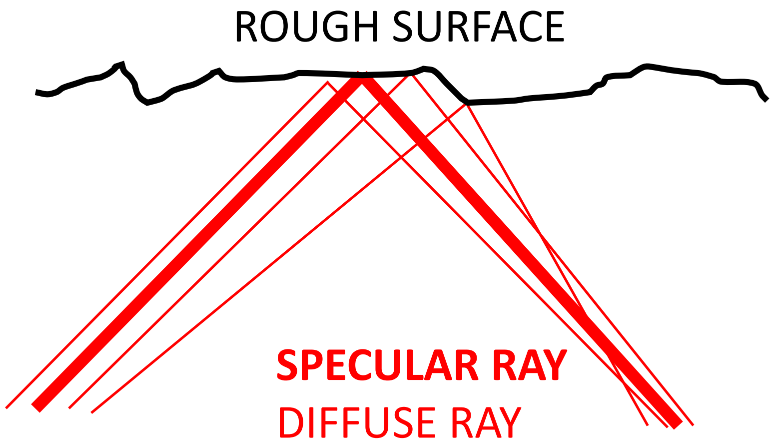
(B): Boulder Campus
(G): Gaithersburg Campus

How are mmWave Channels Different?

- Diffracted rays at mmWave frequencies are very weak/negligible
- Penetration loss at mmWave is so high that rays will not propagate far
- Even free-space pathloss will be significantly higher

} Sparse channel





- At mmWave, surface roughness can be on the order of a wavelength, generating diffuse rays in addition to specular rays

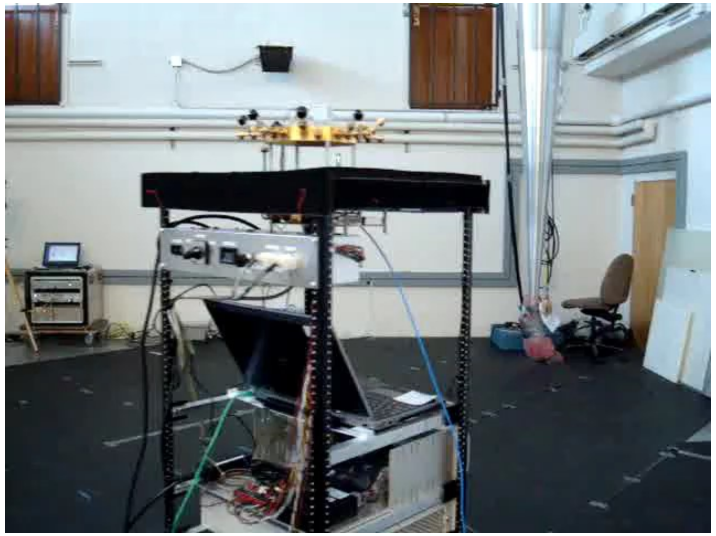
Channel Measurements

Ideal Features of mmWave Channel Sounders

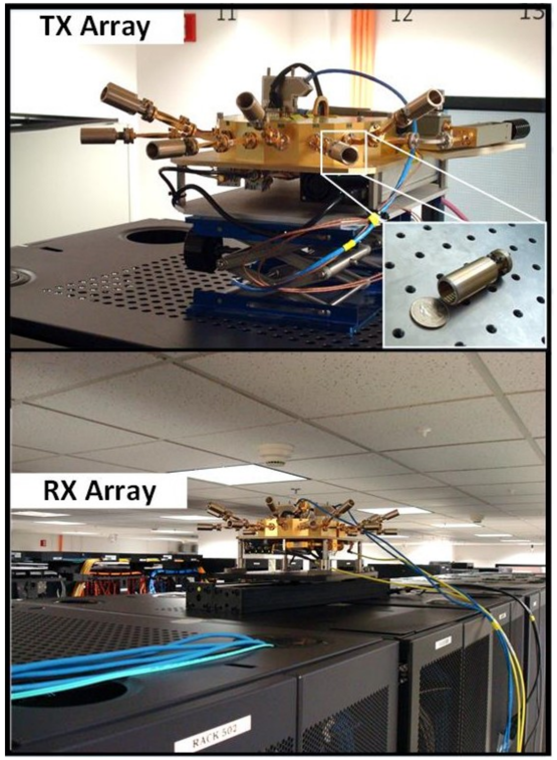
- High antenna gain
- Antenna arrays
- Omnidirectional field-of-view (FoV)
- Dual polarization
- High dynamic range
- Ultra-wide bandwidth
- Fast channel sweep time

NIST Switched-Array Channel Sounders

83-GHz System (video)



60-GHz System

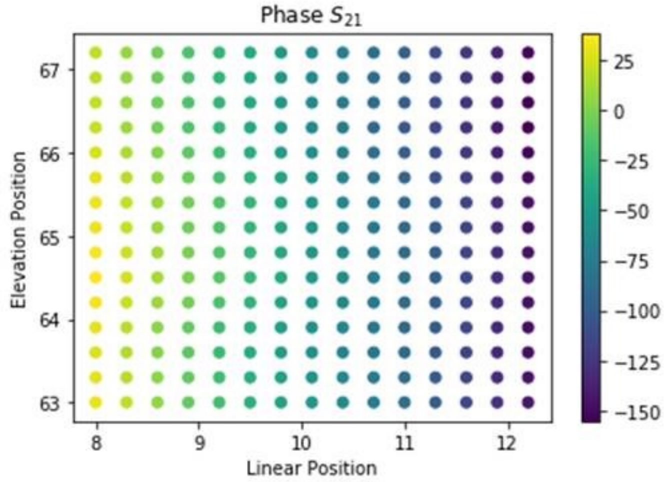


28-GHz System

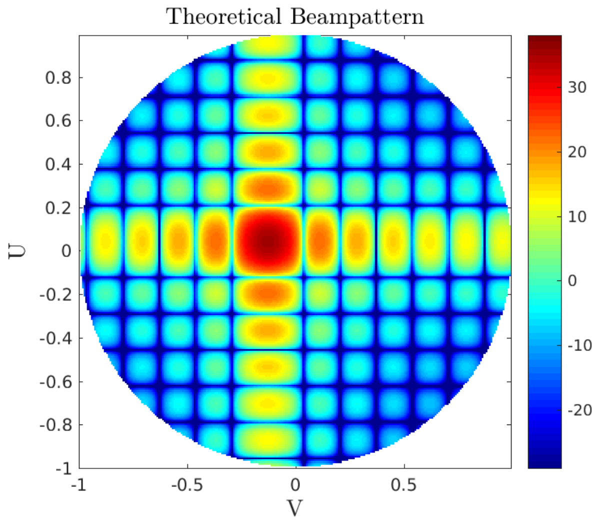
- 16-18 dBi antenna gain
- 2D arrays at both TX and RX
- Omni azimuth FoV at TX and RX
- 45-55 dB dynamic range
- 1-2 GHz bandwidth
- 65-262 us sweep time
- Automated collection system with robot

NIST Virtual-Array Channel Sounder

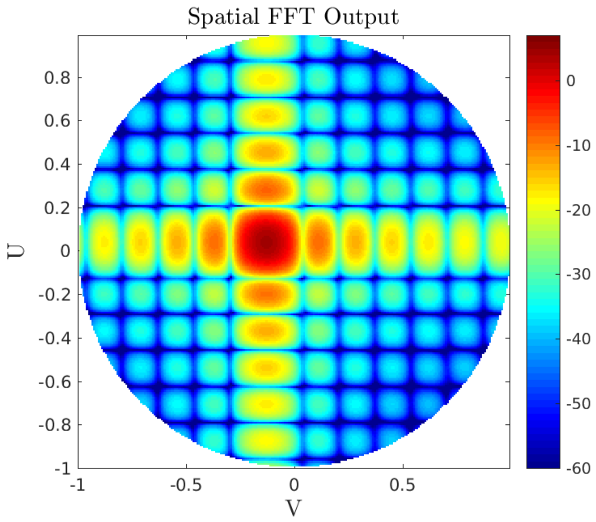
Synthetic aperture samples across space



Simulated array response

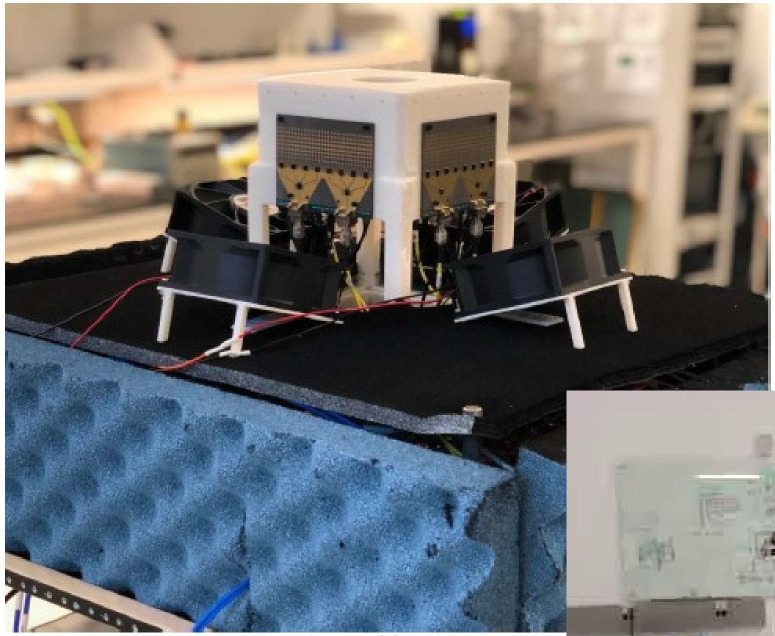


Measured array response



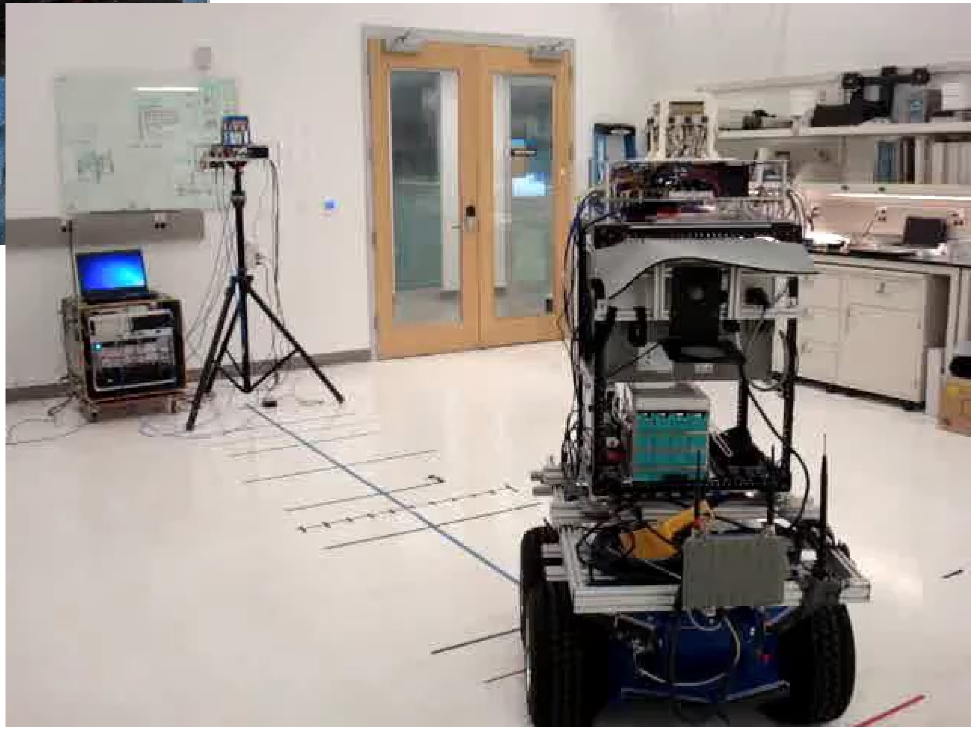
- High angle resolution limited only by span of robotic arm
- Super ultra-wide bandwidth (26-40 GHz)
- No mutual coupling effects
- High dynamic range at each measurement due to VNA
- Digitized signal available at each sample position
- Provides measurement uncertainties

NIST Phased-Array Channel Sounders



60-GHz System:
- Similar properties as virtual array, but FAST!
- 4 ms sweep time
- 26 dBi antenna gain
- 1D arrays 1 GHz bandwidth
- Automated collection system with robot

60-GHz System



28-GHz System also has:
- dual polarization
- 2D arrays

Channel Modeling

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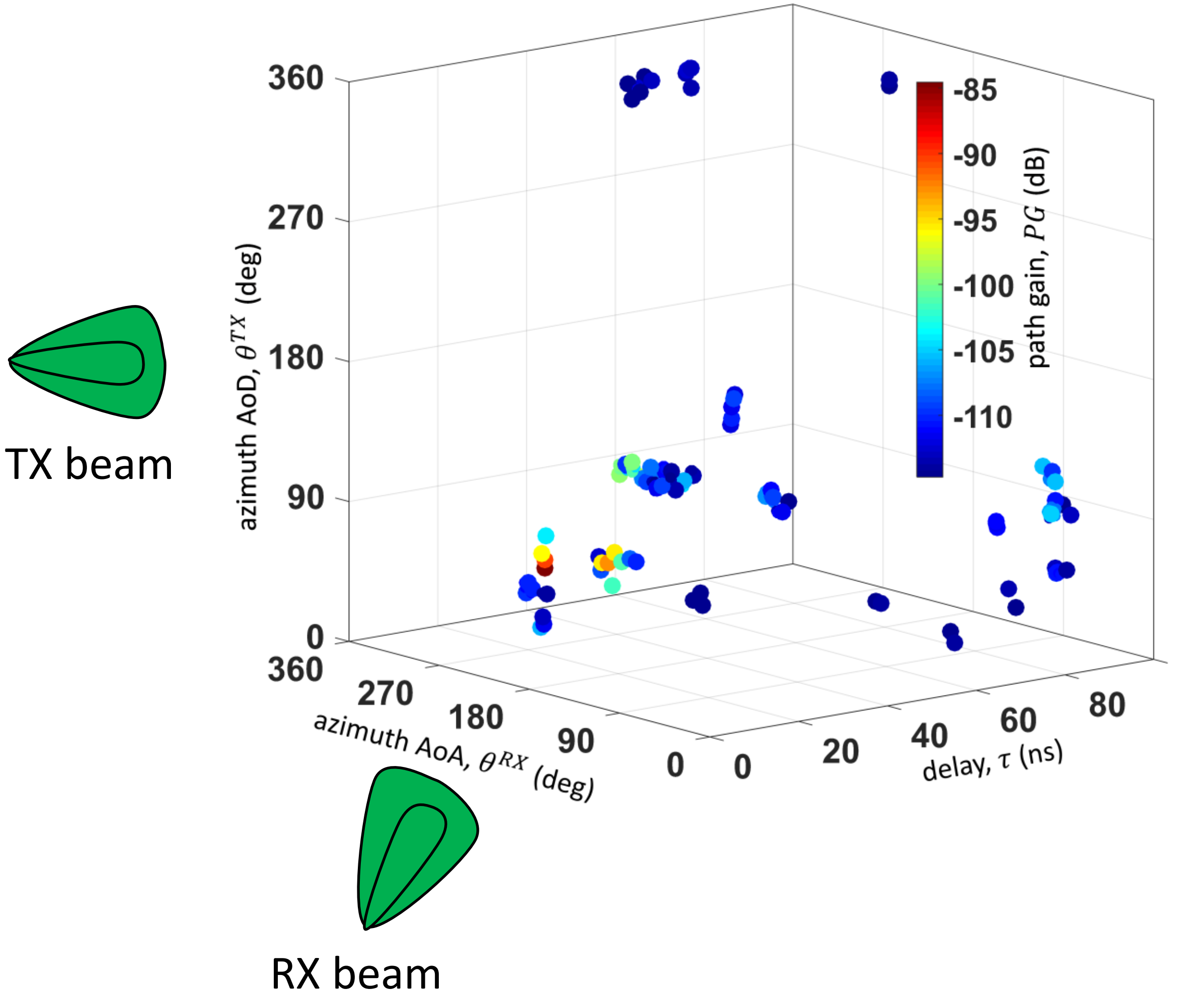
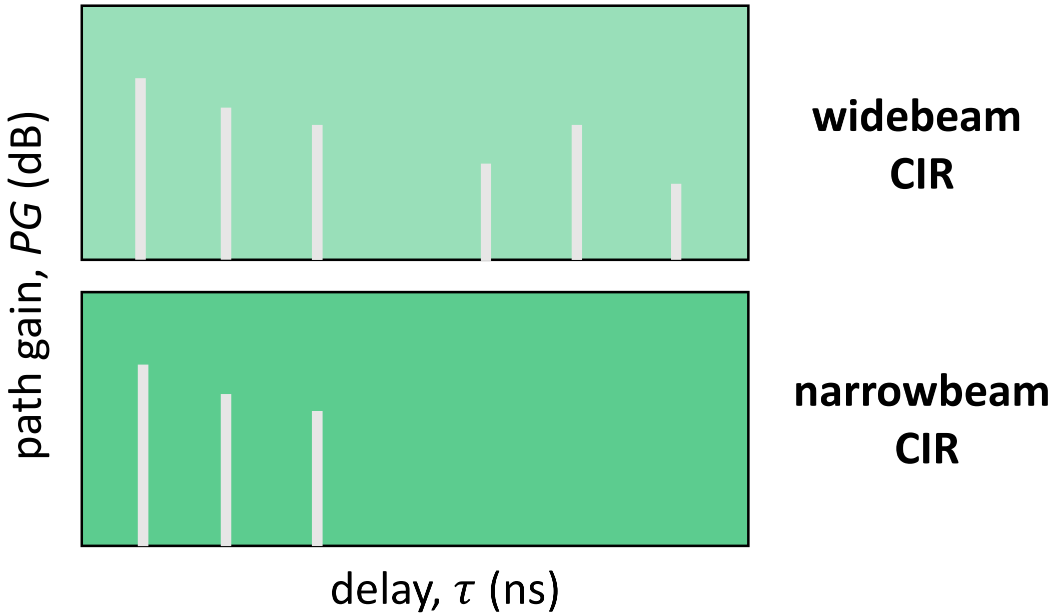
Dispersion Models

Rays extracted from measurement in a lecture room with 60-GHz switched-array system

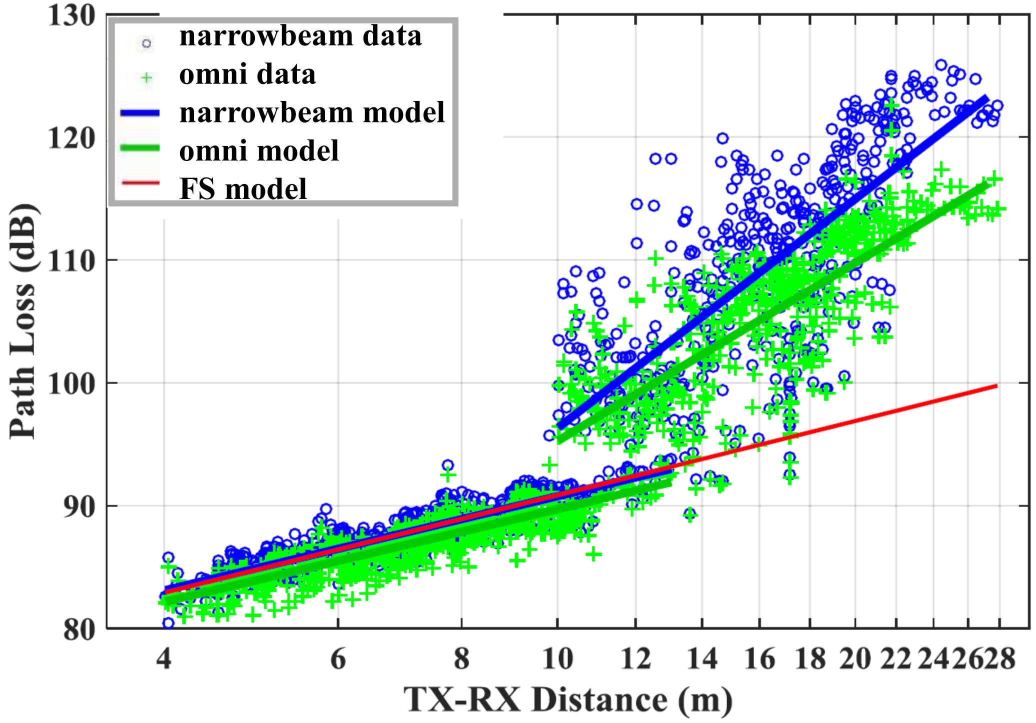




- Dispersion models describe how channel rays are dispersed in delay and angle
- Before 5G, delay dispersion only was necessary because omni antennas would detect all rays
- For 5G, angle dispersion is also necessary to determine which rays the pencilbeams will detect

Beamwidth-Dependent Pathloss Models

Pathloss data from measurement in lobby/hallway with 83-GHz switched-array system



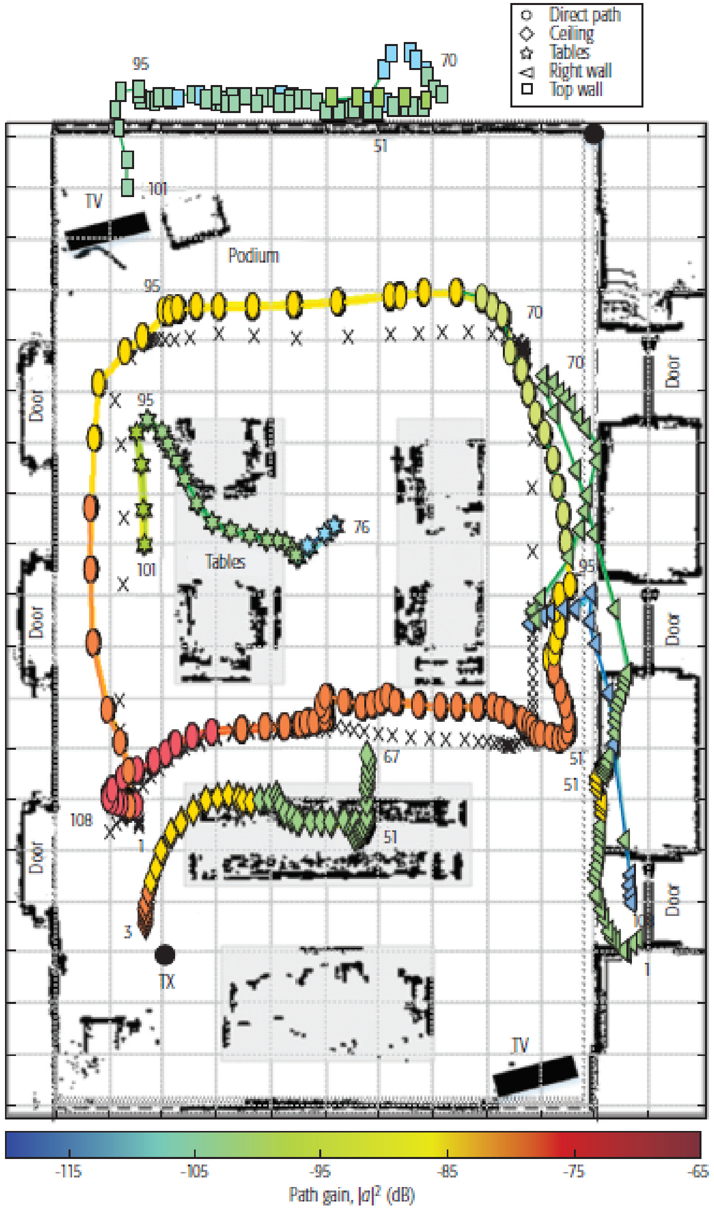
Pathloss-model parameters for various indoor environments at 83 GHz

Environment	d_1 (m)	α_0	β_0 (dB)	σ_0 (dB)	α_1	β_1 (dB)	σ_1 (dB)
Basement		**1.97**	**71.18**	**1.09**			
		1.96	69.80	0.86			
Hallway	26.3	**1.87**	**72.87**	**0.71**	**1.51**	**-0.99**	**2.81**
		1.60	73.77	0.98	1.36	-0.47	1.92
Lobby / Hallway TX1	10.1	**2.37**	**67.87**	**2.34**	**7.45**	**2.66**	**3.87**
		2.39	66.85	1.73	5.30	3.94	2.28
Lobby / Hallway TX2	7.8	**1.75**	**73.26**	**1.13**	**4.21**	**14.92**	**3.74**
		1.46	74.66	1.22	3.00	12.96	1.92
Lobby / Hallway TX3	11.3	**1.87**	**72.00**	**1.25**	**6.16**	**8.44**	**3.04**
		1.90	70.41	1.41	5.52	7.09	2.03
Lobby / Hallway TX4	13.3	**2.05**	**70.16**	**1.27**	**4.38**	**4.40**	**5.35**
		2.05	69.34	1.10	4.11	3.48	3.83
Lobby / Hallway TX5	9.9	**1.57**	**74.49**	**1.19**	**3.35**	**6.10**	**5.08**
		1.68	72.70	1.19	3.00	5.38	3.73
Lobby / Hallway floating		**1.93**	**71.51**	**1.52**	**6.19**	**5.54**	**5.82**
		1.90	70.73	1.40	4.81	5.64	4.06
Lobby / Conf. Room Open	7.3				**5.75**	**10.54**	**3.20**
					3.63	10.10	2.12
Lobby / Conf. Room Closed					**0.00**	**33.60**	**2.21**
					0.04	25.90	1.43

- Pathloss models can be beamwidth dependent by admitting more/less rays into the beam
- The pathloss exponent – especially in NLOS – can vary significantly between narrowband and widebeam systems

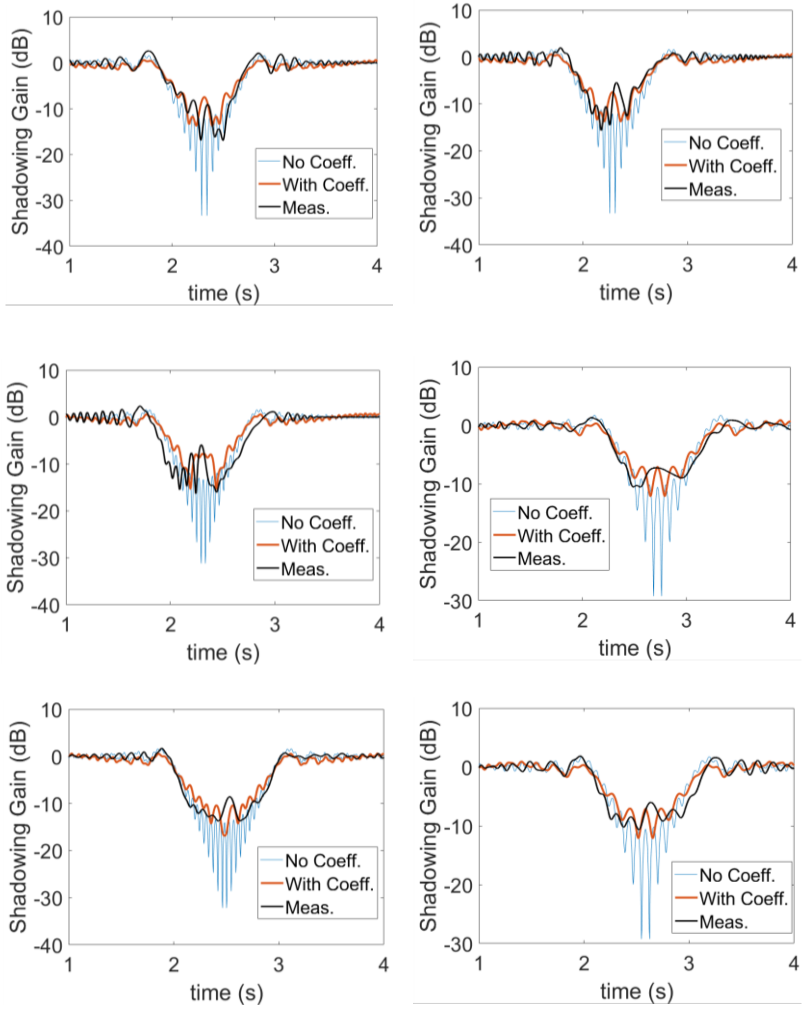
Ray Tracking

Measurements with 60-GHz switched-array system in lecture room

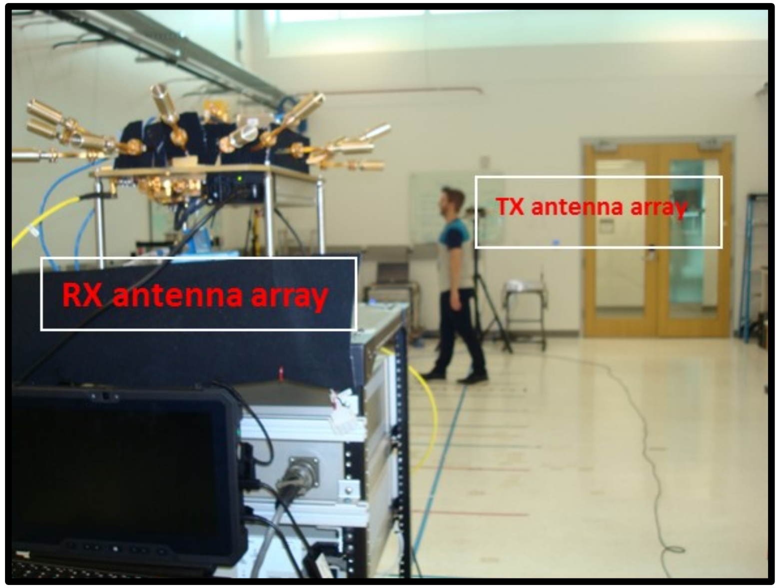


- 5G systems will steer beams towards channel rays
  - recover from blockage
  - exploit multiple rays for spatial multiplexing
- Understand how ray properties (path gain, AoD, AoA) change in time and space
- Understand which ambient objects can serve as persistent reflectors

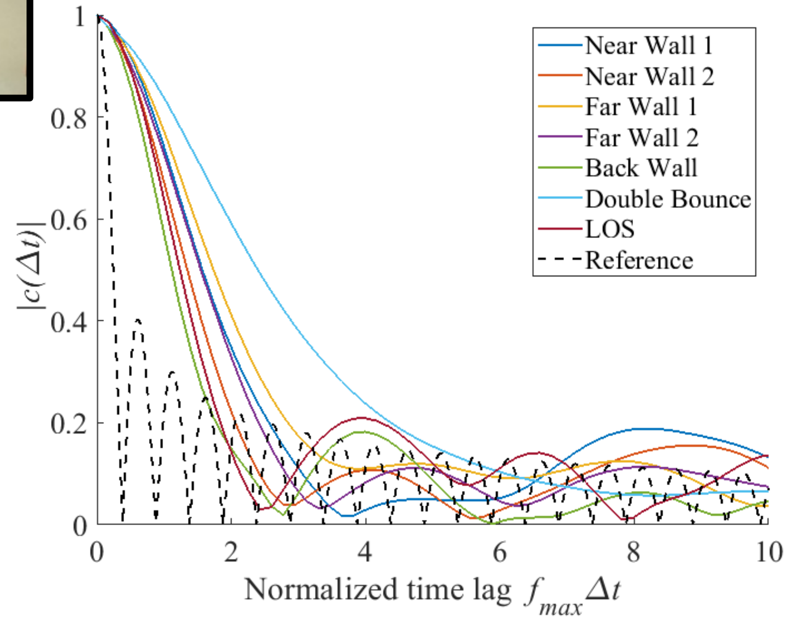
Our Systems Can Support Almost Any Channel Model



Human presence models



60-GHz switched-array system



Fast-fading models

Collaborations with Industry: Select Examples

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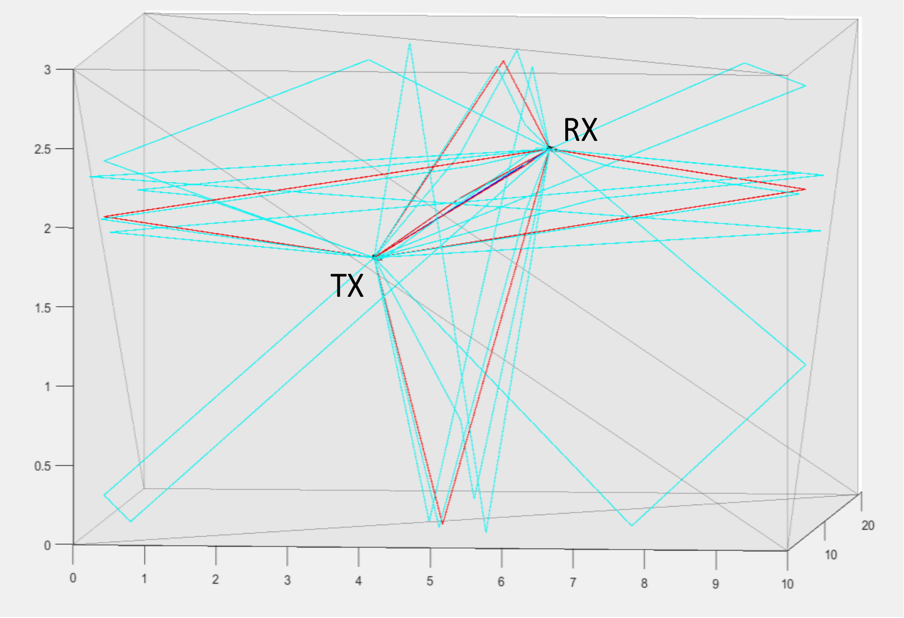
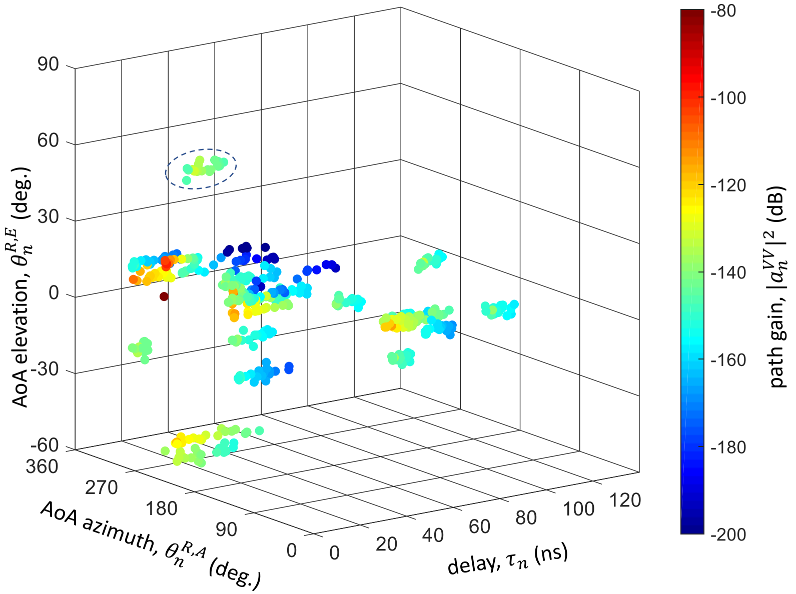
IEEE: Contributions to 802.11ay

Contributed three new models to IEEE 802.11ay channel modeling document:

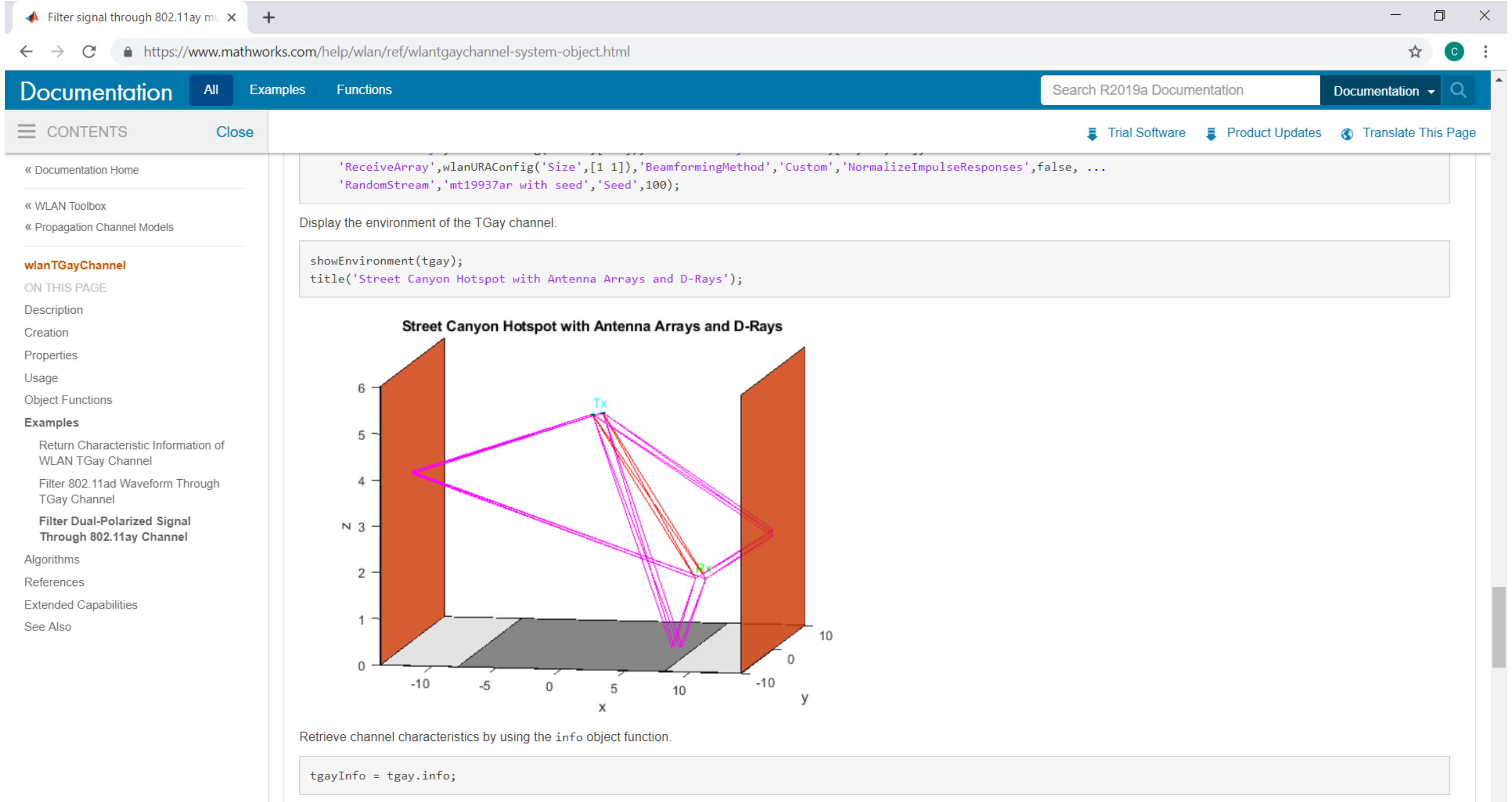
- A. Malstev,…, C. Gentile, P. Papazian, J.-K. Choi, J. Senic, J. Wang, D. Lai, N. Golmie, K. Remley, et al., “Channel Models for IEEE 802.11ay,” Document IEEE 802.11-15/1150r9, March 2017.
    - Quasi-Deterministic Model for Lecture Room
    - Quasi-Deterministic Model for Data Center
    - Quasi-Deterministic Model for Doppler Spread





Visualization of Quasi-Deterministic Model

Mathworks: IEEE 802.11ay Channel Model



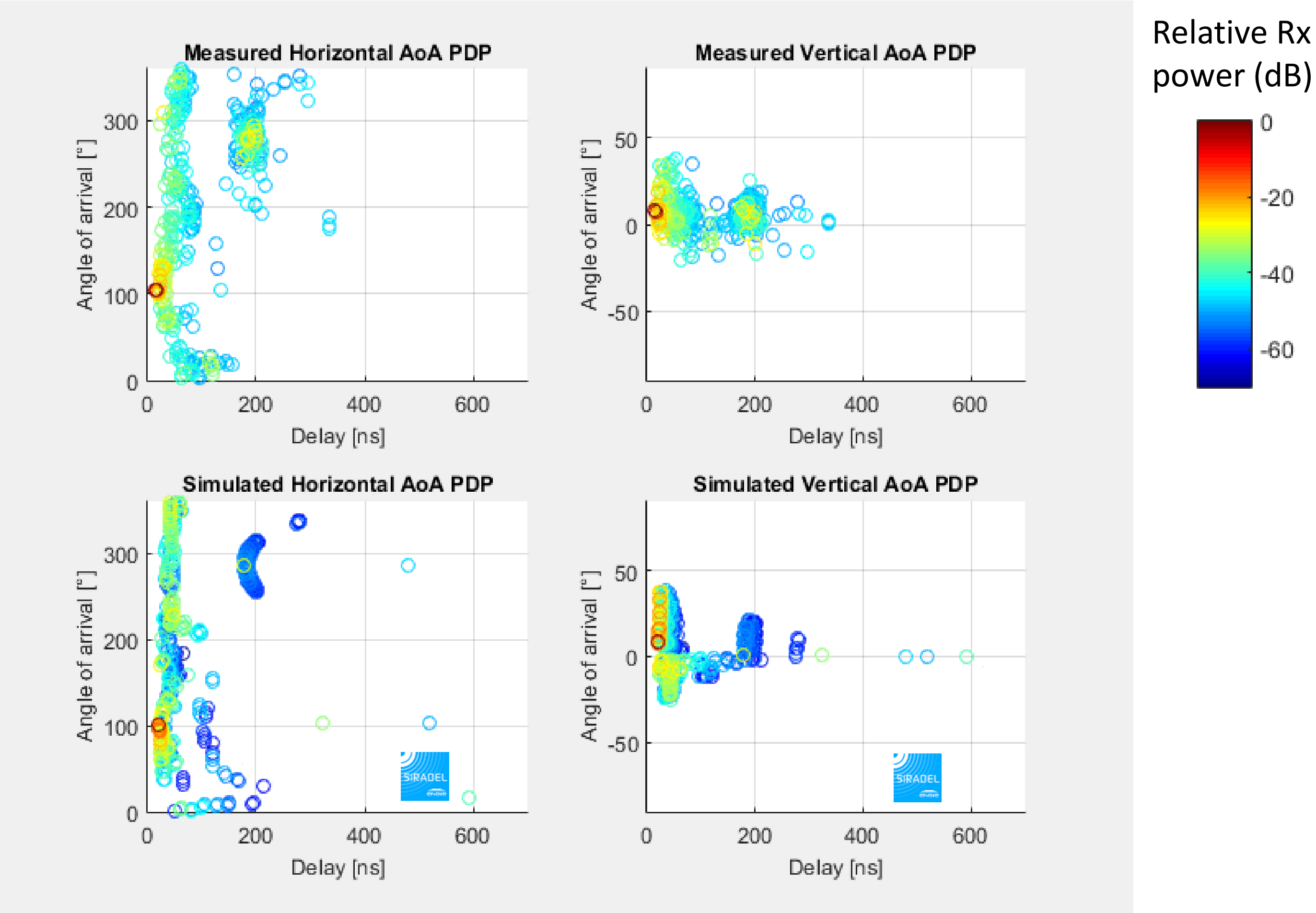
IEEE 802.11ay documentation page in MATLAB

Integration of IEEE 802.11ay channel models in MATLAB release 2018b

- Collaborated with MATLAB engineers for over one year
- Provided prototype code to help them with implementation

Siradel*: Tuning of Raytracing Engine

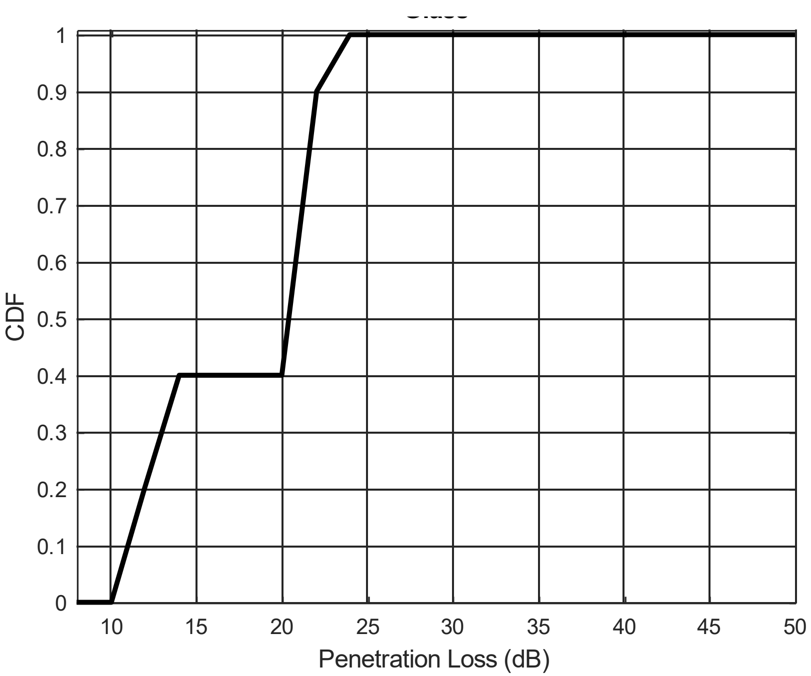
Tuning of Siradel's *Volcano* raytracing engine against NIST measurements



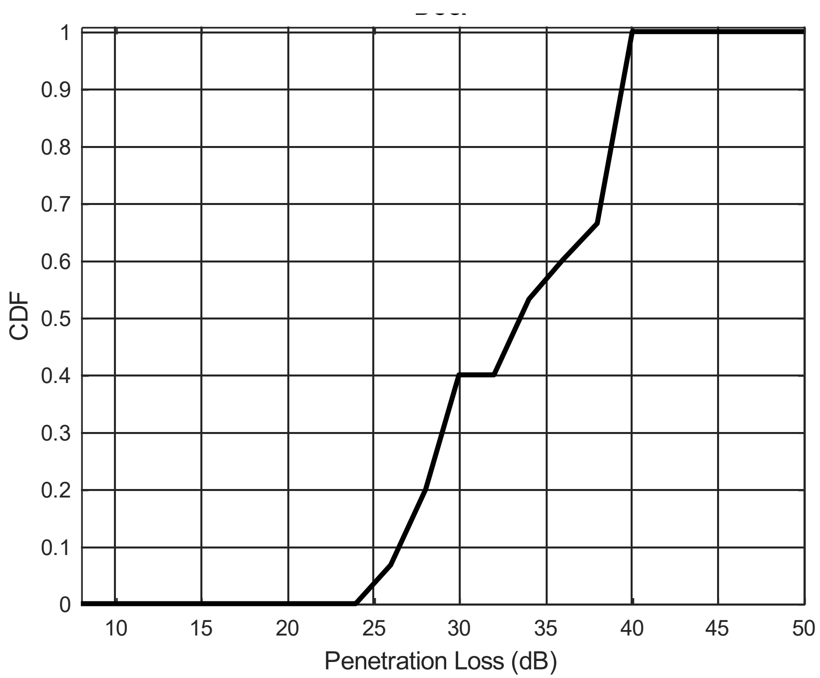
NIST 28-GHz measurements in downtown Boulder

*Siradel is an RF planning tool company with headquarters in North America, Europe, and Asia

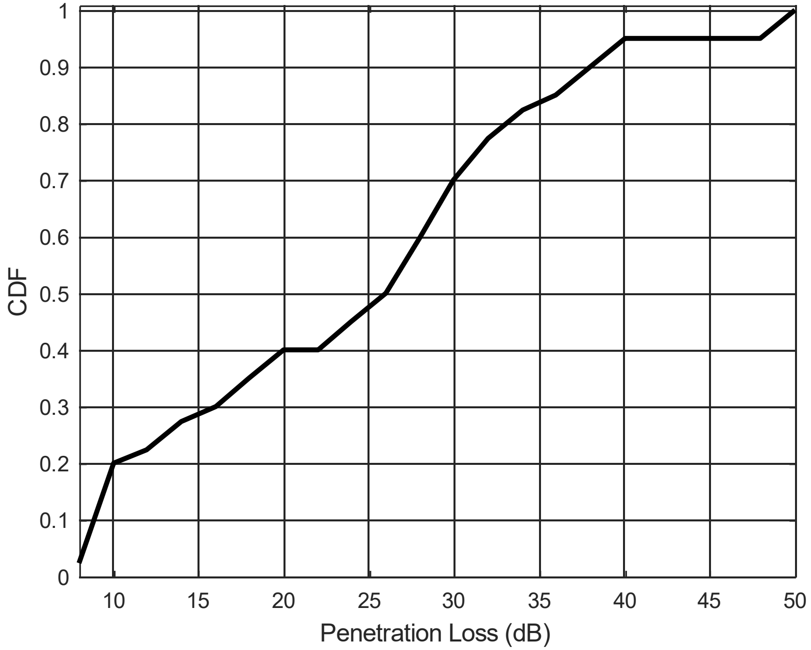
Qualcomm: Indoor Penetration Loss



Glass



Wooden Door



Dry Wall with Studs

Measurements of indoor penetration loss with NIST 60-GHz switched-array channel sounder

- Collected over 100 measurements in minutes
- Penetrations through multiple wall materials in hallway

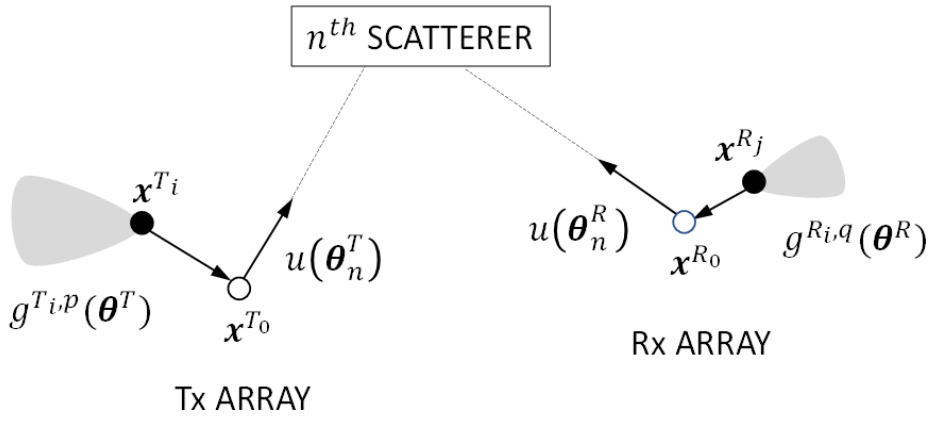
5G mmWave Channel Model Alliance

- **Book:** “Millimeter-Wave Channel Modeling and Measurement Approaches”, Prentice-Hall, 2020

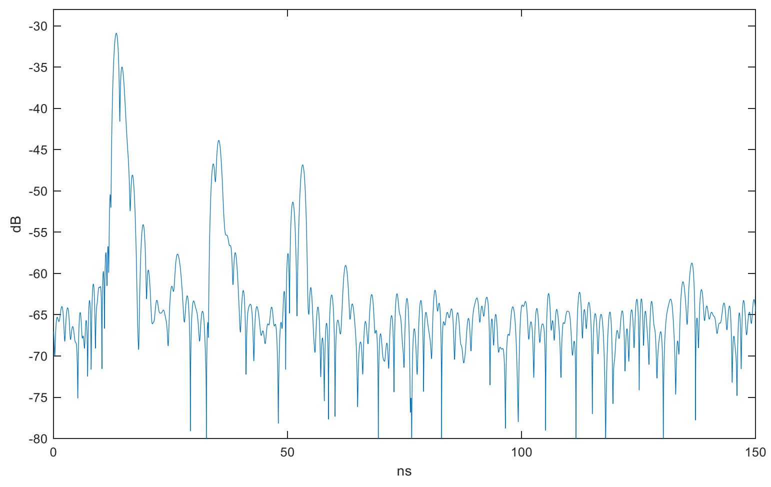
- **Data repository:**
- Over 80 registered
- *Over 20 data sets across multiple* mmWave bands from 5 different organizations

- **Practical methodology to benchmark RF channel sounders:**

-Participation from five worldwide research organizations (NIST, U. British Columbia, U. of Southern California, U. of Ilmenau, North Carolina State U.)
- Mathematical model to represent channel sounder whose parameters are characterized through in situ measurements
- Benchmark performance of channel sounders against identical channel



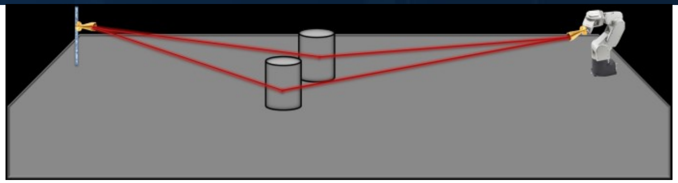
Channel sounder model



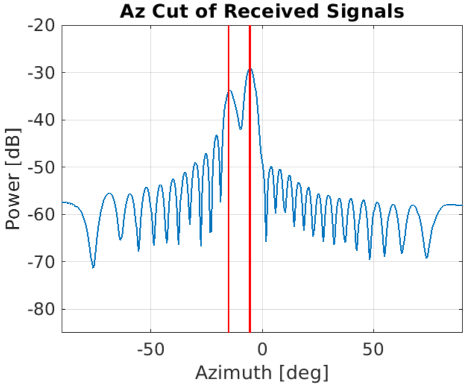
Simulated measurement for NIST 28-GHz switched-array channel sounder

5G mmWave Channel Model Alliance (cont)

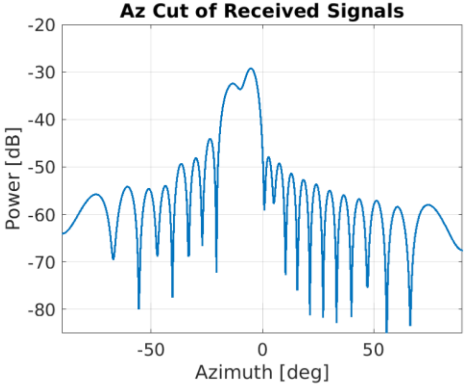
- Channel-Sounder Hardware Verification:
  - NIST artifacts provide repeatable channels:
    - Multipath channel (conducted)
    - Spatial channel (over the air)
  - NIST provides reference measurement
  - Users' hardware, processing code checked



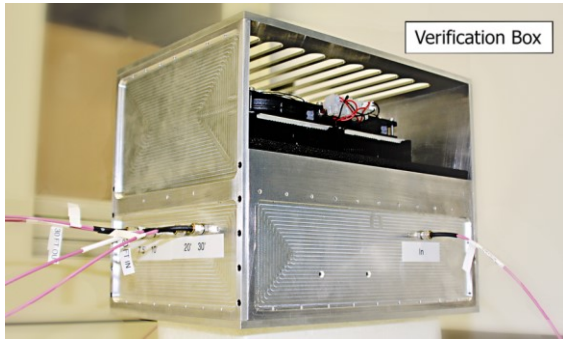
Angle-of-arrival verification artifact (wireless channel)



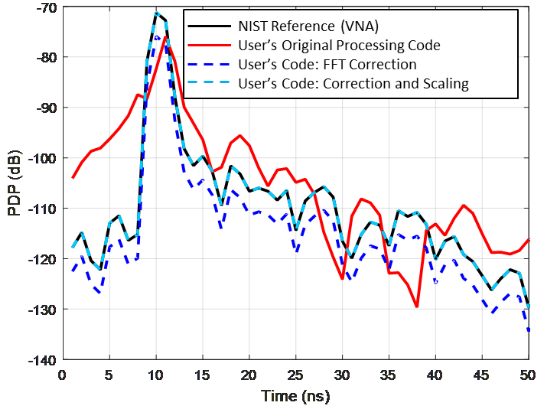
40 GHz: AoA resolvable



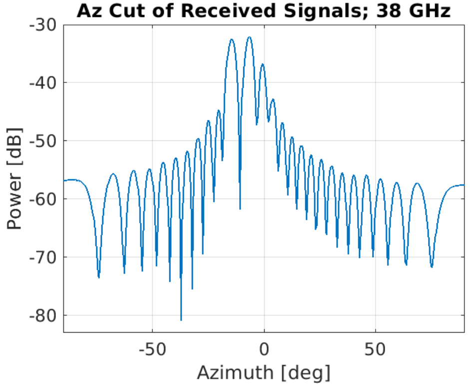
31 GHz: AoA not resolvable



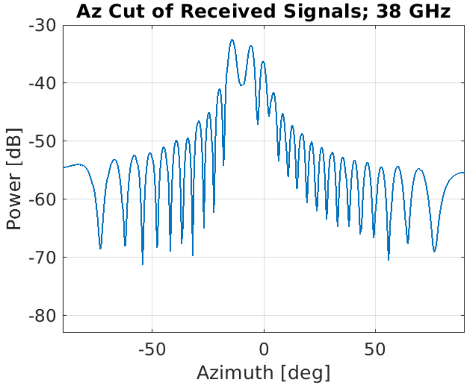
Multipath verification artifact (conducted channel)



User's processing code improved using NIST artifact

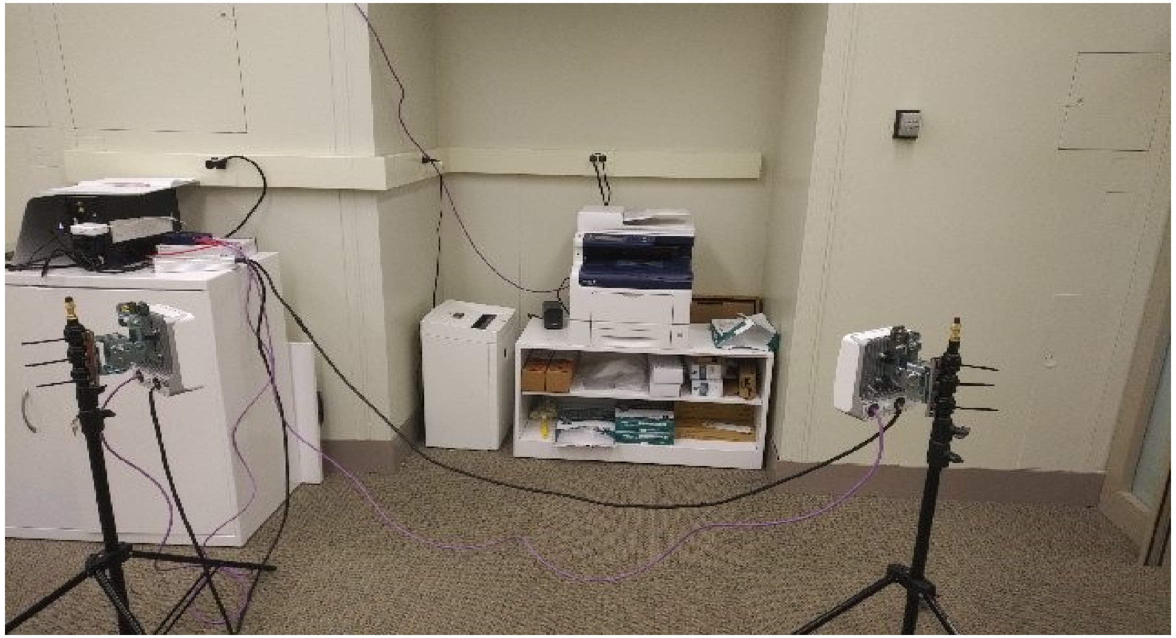


340 mm: AoA resolvable



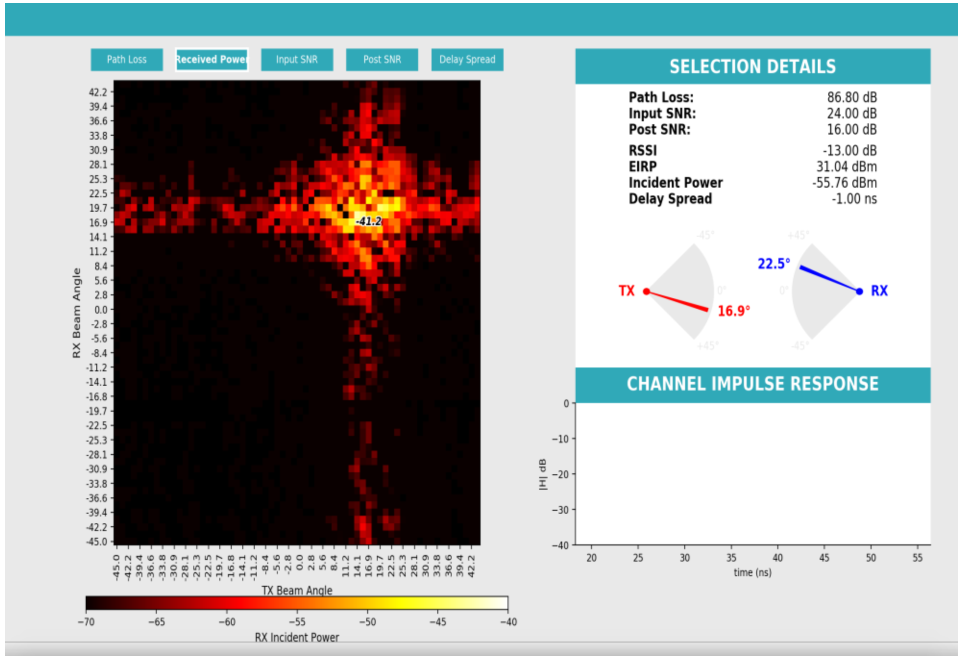
320 mm: AoA not resolvable

Facebook: 802.11ad-Based Sounder



Testing with sounder at NIST Gaithersburg

- Facebook in collaboration with TIP[1] (Telecom Infra Project) and Telefar Co[2] is distributing an 802.11ad-based phased-array sounder at 60-GHz
- Intention is to amass lots of measurement data collected from organizations across the globe to understand mmWave propagation better
- NIST is participating in study
- Data will be disseminated through 5G Alliance website



[1]https://telecominfraproject.com/
[2]https://www.telefarco.com/

High Fidelity mmWave System-Level Modeling & Simulation

National Institute of Standards and Technology
U.S. Department of Commerce

CTL Communications Technology Laboratory

High Fidelity System-Level Modeling

Channel Propagation Measurements — *Channel Sounders*

Channel Model — *Multi-path Components*

Quasi-Deterministic Realization software* (60 GHz) — *Matlab*

Matlab

Link level simulation
PHY layer model for IEEE 802.11ay

IEEE 802.11ay PHY layer abstraction

Channel Model parameters (MPC, Angles, Delay, etc.)

ns-3 802.11ad/ay implementation with Q-D channel model*

System-Level Protocol Evaluation

* Publicly Available*: https://github.com/wigig-tools*

System-Level Protocol Evaluation

ns-3 802.11ad/ay implementation with Q-D channel model

Beam management

Beamforming Training

SLS (Sector Level Sweep)

BRP (Beam Refinement Protocol)

Beamforming Tracking

Design/evaluate beam management algorithms:
- **Antenna array geometry**
- **Mobility models**
- **Environment specifics**

Data Transmission

Hybrid MAC

CBAP

SP

Design/evaluate schedulers for specific applications/environments

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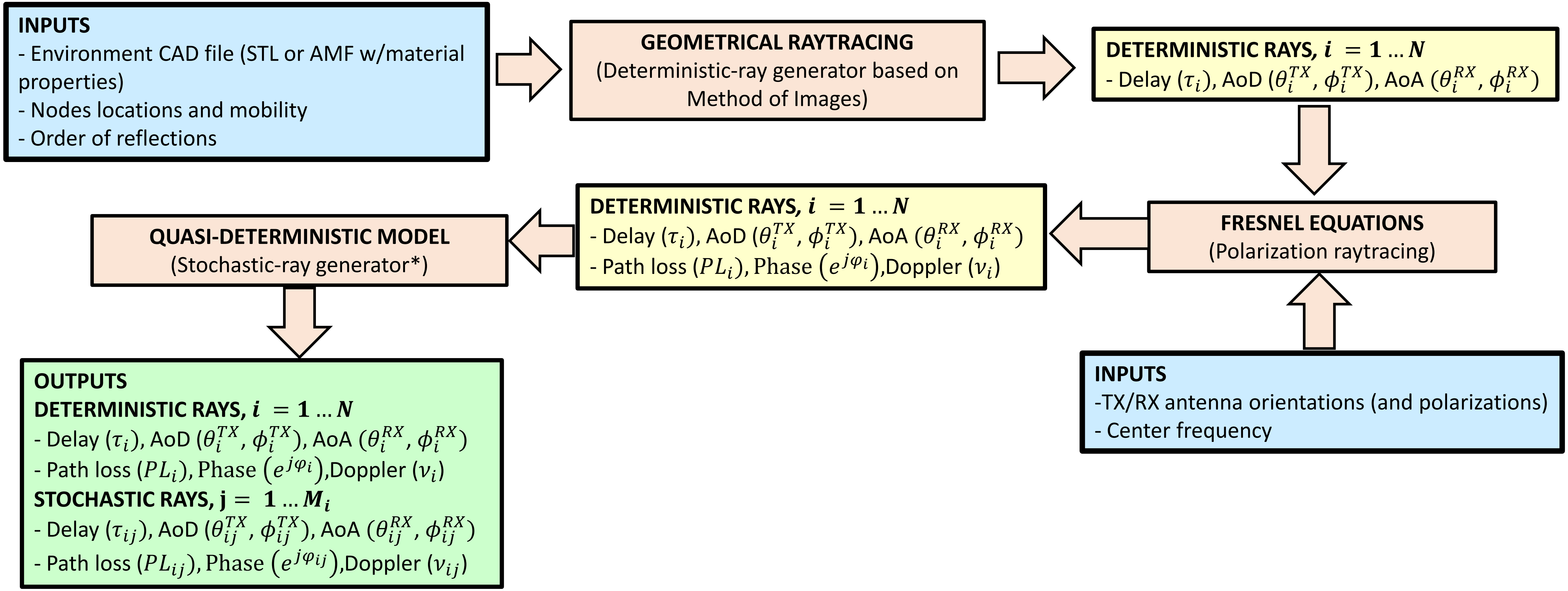
Appendix

Q-D Realization Software



Publicly available at: https://github.com/wigig-tools

** The stochastic ray-generator is based on the lecture-room measurement campaign in IEEE P802.11 Group for Wireless Local Area Networks (LANs). 2017 Channel Models for IEEE 802.11ay.*

ns-3 802.11ad/ay implementation with Q-D channel model

802.11ad ns-3 module has been modified to:

- Implement the Q-D channel model
- Be able to use any kind of phased array antenna

Codebook Generator*

INPUTS
- Phased array antenna geometry
- Antenna elements type

OUTPUTS
- Codebook file for APs and STAs (steering vector and complex AWV per sector)

Q-D Realization software

INPUTS
- Environment CAD file
- Nodes locations and mobility
- Order of reflections

OUTPUTS
- Q-D files representing the channel, i.e, MPCs parameters

ns-3 802.11ad/ay implementation with Q-D channel model

$$\boldsymbol{h_{BF}} = \sum_{i=0}^{N-1} \left(\boldsymbol{A}^{(i)} \left(\boldsymbol{Y}_{Rx}^{(i)} \, \boldsymbol{Y}_{Tx}^{(i)} \right) \boldsymbol{e}^{-j2\pi f t_i} \right)$$

- $\boldsymbol{N}$: number of MPCs
- $\boldsymbol{A}^{(i)}$: Complex amplitude of the i^th MPC
- $\boldsymbol{Y}_{Rx}^{(i)}$ *and* $\boldsymbol{Y}_{Tx}^{(i)}$: radiation pattern of the receiver and transmitter array at the i^th MPC respectively
- $\boldsymbol{f}$: operational frequency
- $\boldsymbol{t_i}$: delay for the ith MPC

** Matlab code provided by IMDEA*

802.11ay PHY layer abstraction (error curves)

Q-D Realization software

Analog Beamforming

Beamform multi-path components (MPCs) along the directions of 7 dominant paths (direct, 4 walls, ceiling and ground)

System Requirements

- Transmission modes (Control, SC, OFDM)
- SISO/MIMO configurations
- System parameters (channel bandwidth, packet length, etc.)

NIST IEEE 802.11ay PHY Layer*

NIST Error Model
(BER/SNR curves)

Mapping methods

- Exponential Effective SNR Mapping
- Mean Mutual Information per Bit
- Q-Mapping

ns-3 802.11ad/ay implementation with Q-D channel model

*based on Matlab DMG IEEE 802.111ad WLAN System Toolbox