# A Novel Millimeter-Wave Channel Simulator (NYUSIM) and Applications for 5G Wireless Communications

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S. Sun, G. R. MacCartney, Jr., and T. S. Rappaport, "A novel millimeter-wave channel simulator and applications for 5G wireless communications," *2017 IEEE International Conference on Communications (ICC)*, Paris, May 2017.

# Agenda

- Background and Motivation
- Main features of NYUSIM
- Channel Model Supported by NYUSIM
- Graphical User Interface and Simulator Basics
- Applications of NYUSIM for millimeter-wave MIMO system analysis and design
- Conclusions

# Background and Motivation

- **Construction and implementation of channel models are important for wireless communication system design, and channel simulators are in great need**

- **Existing channel simulators: QuaDRiGa, SIRCIM, SMRCIM, BERSIM, NS-3, etc.**

- **No channel simulators exist that are developed based on extensive propagation measurements at centimeter-wave to millimeter-wave (mmWave) bands in various scenarios for fifth-generation (5G) wireless communications**

S. Jaeckel et al., “QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 6, pp. 3242–3256, June 2014.
T. S. Rappaport et al., “Statistical channel impulse response models for factory and open plan building radio communicate system design,” IEEE Transactions on Communications, vol. 39, no. 5, pp. 794–807, May 1991.
Wireless Valley Communications, Inc., SMRCIM Plus 4.0 (Simulation of Mobile Radio Channel Impulse Response Models) Users Manual, Aug. 1999.
V. Fung et al., “Bit error simulation for pi/4 DQPSK mobile radio communications using two-ray and measurement-based impulse response models,” IEEE Journal on Selected Areas in Communications, vol. 11, no. 3, pp. 393–405, Apr. 1993.

# Main Features of NYUSIM

**NYUSIM is a MATLAB-based open-source channel simulator developed by NYU WIRELESS, which has the following main features:**

- Built based on **extensive mmWave measurements** from 2012 through 2017 at frequencies from 2 to 73 GHz in various outdoor environments in urban microcell (UMi), urban macrocell (UMa), and rural macrocell (RMa) environments
- Provides an accurate rendering of actual channel impulse responses in both time and 3D space (**including the elevation dimension**), as well as realistic signal levels that were measured
- Applicable for a wide range of carrier frequencies from 500 MHz to 100 GHz, selectable RF bandwidths up to 800 MHz, and continually adjustable antenna beamwidths
- Has been downloaded over 7,000 times
- We provide user support and updates of NYUSIM per users' feedback


T. A. Thomas, M. Rybakowski, S. Sun, T. S. Rappaport, H. Nguyen, I. Z. Kovács, I. Rodriguez, "A Prediction Study of Path Loss Models from 2-73.5 GHz in an Urban-Macro Environment," *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, Nanjing, 2016, pp. 1-5.

T. S. Rappaport et al., "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

T. S. Rappaport et al., "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (Invited Paper)," *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029–3056, Sep. 2015.

M. K. Samimi and T. S. Rappaport, "3-D millimeter-wave statistical channel model for 5G wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, July 2016.

S. Sun et al., "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843–2860, May 2016.

G. R. MacCartney, Jr. et al., "Millimeter wave wireless communications: New results for rural connectivity," in *All Things Cellular16, in conjunction with ACM MobiCom*, Oct. 2016.

# Channel Model Supported by NYUSIM

- 3D Statistical Spatial Channel Model (SSCM) developed from extensive field measurements at mmWave frequencies
- Key components of SSCM
  - LOS probability model
  - Large-scale path loss model
  - Large-scale parameters: omnidirectional RMS delay spread, angular spreads (azimuth and elevation angles of departure (AoDs) and angles of arrival (AoAs)), and shadow fading
  - Small-scale parameters: time cluster (TC) delay, subpath delay, TC power, subpath power, spatial lobe (SL) AoD and AoA, subpath AoD and AoA
- To obtain TCs and SLs, a TCSL clustering algorithm was used based on field observation (detailed in Slide 7)

| Name of Parameter | Distribution |
|---|---|
| Number of Time Clusters | Discrete Uniform [1, 6] |
| Number of Subpaths | Discrete Uniform [1, 30] |
| Cluster Delays, Powers | Exponential, Lognormal |
| Subpath Delays, Powers | Exponential, Lognormal |
| Subpath Phases | Uniform $(0,2\pi)$ |
| Number of Spatial Lobes (AOD & AOA) | Poisson |
| Lobe Az./El. Angles (AOD & AOA) | Uniform (0, 360), Gaussian |
| RMS Lobe Az./El. Spreads (AOD & AOA) | Gaussian, Laplacian |

M. K. Samimi and T. S. Rappaport, "3-D millimeter-wave statistical channel model for 5G wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, July 2016.

Time clusters: varies from 1 to 6 in a uniform manner

Spatial lobes: Poisson distribution with an upper bound of 5

# Path Loss Model Supported by NYUSIM



- **Close-in Free Space Reference Distance (CI) Model**

$$\mathrm{PL}^{\mathrm{CI}}(f, d_{3\mathrm{D}})[\mathrm{dB}] = \mathrm{FSPL}(f, 1\ \mathrm{m})[\mathrm{dB}] + 10n\log_{10}(d_{3\mathrm{D}}) + \chi_{\sigma}^{\mathrm{CI}}$$

$$= 20\log_{10}\left(\frac{4\pi f \times 10^9}{c}\right) + 10n\log_{10}(d_{3\mathrm{D}}) + \chi_{\sigma}^{\mathrm{CI}}$$

$$= 32.4 + 10n\log_{10}(d_{3\mathrm{D}}) + 20\log_{10}(f) + \chi_{\sigma}^{\mathrm{CI}}$$

$$\text{where } d_{3\mathrm{D}} \geq 1\ \mathrm{m}$$

  - $n$ **is the path loss exponent (PLE)**
  - **Only one parameter ($n$, or PLE) needs to be optimized**
  - **Least squares method to minimize** $\sigma$

G. R. MacCartney, Jr., T. S. Rappaport, S. Sun and S. Deng, "Indoor Office Wideband Millimeter-Wave Propagation Measurements and Channel Models at 28 and 73 GHz for Ultra-Dense 5G Wireless Networks," *IEEE Access*, vol. 3, pp. 2388-2424, 2015.
S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 1-18, May 2016.

# Clustering Algorithm Supported by NYUSIM



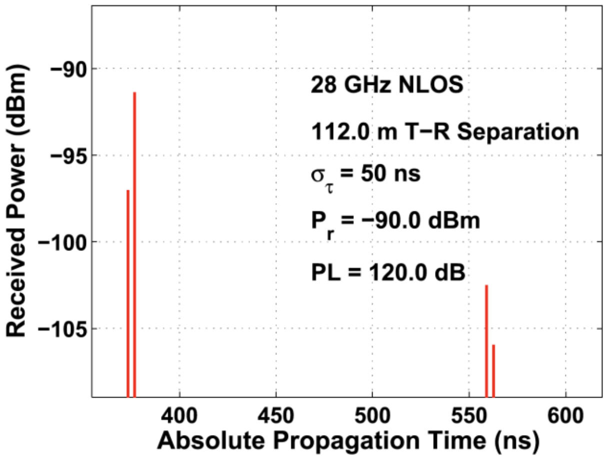
Clustering approach: **Time Cluster – Spatial Lobe (TCSL)**
The TCSL clustering approach matches 1 Terabytes of data obtained from extensive mmWave field measurements

Time cluster: composed of multipath components traveling closely in time

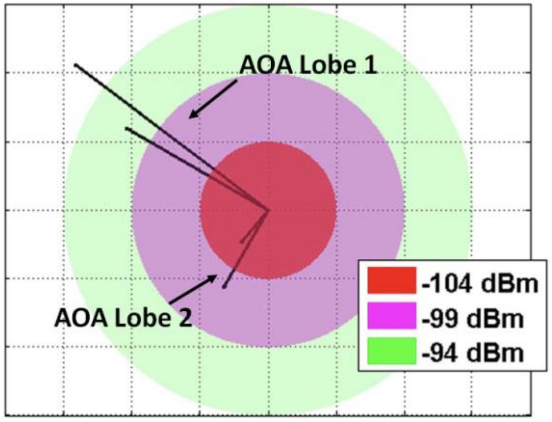
Spatial lobe (3D): main directions of arrival (or departure) over both azimuth and elevation dimensions where energy arrives over several hundred nanoseconds

These definitions are motivated by field measurements, and the TCSL method extracts/decouples the temporal and spatial statistics separately.

Sample Omni. PDP Output Function



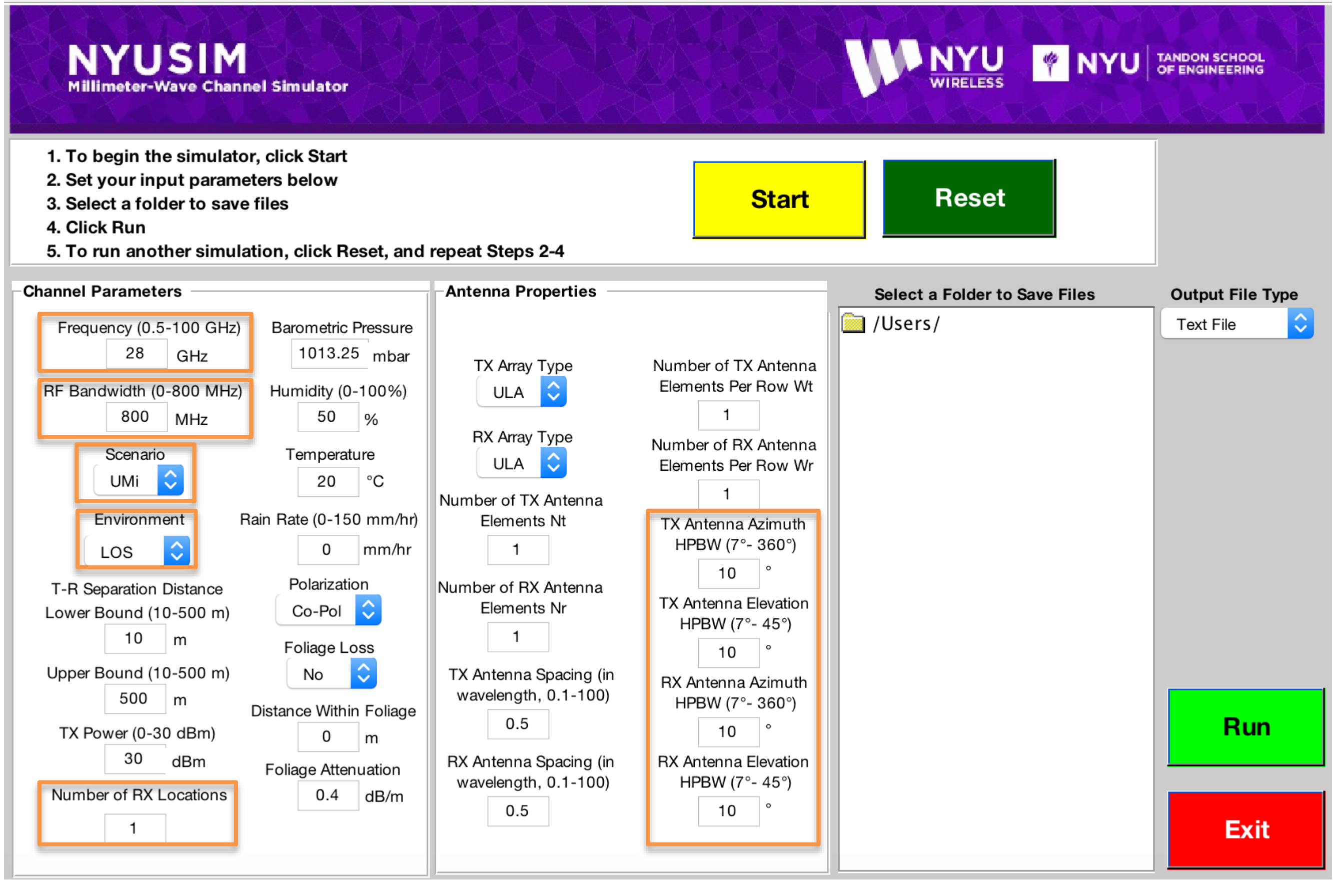

3-D AOA Power Spectrum - 28 GHz NLOS




Top View of Azimuth Plane

M. K. Samimi and T. S. Rappaport, "3-D millimeter-wave statistical channel model for 5G wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, July 2016.

# Graphical User Interface (GUI) of NYUSIM




Easy to select/set input parameters

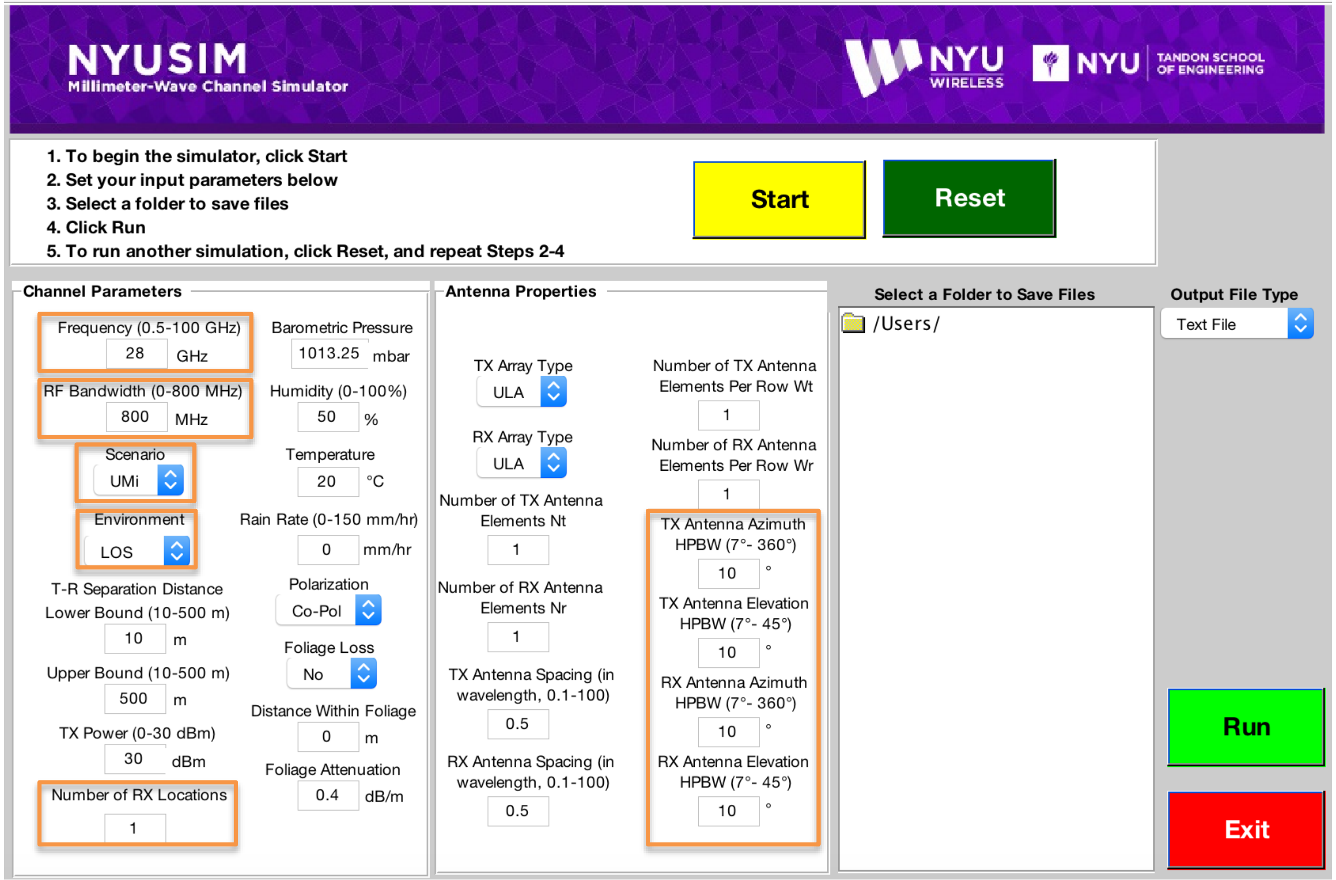
Able to quickly generate channel impulse responses

Three output file type options:
- .txt file
- .mat file
- Both .txt and .mat files

28 input parameters
- Channel Parameters: 16 input parameters
- Antenna Properties: 12 input parameters

Users can perform many continuous simulation runs with identical input parameters for automatically varied uniformly random T-R separation distances

# Flexible Antenna Settings in NYUSIM




The **HPBW** in the input parameters is for the **entire antenna array**

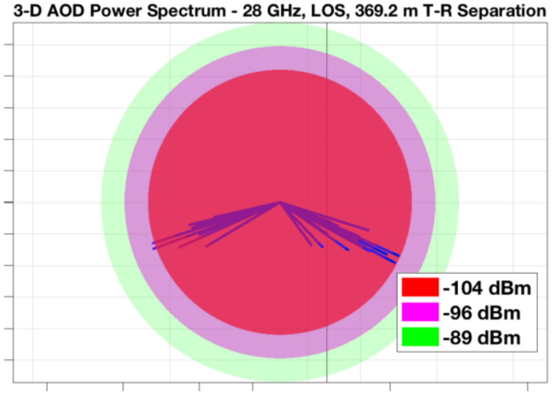
**Advantages:**

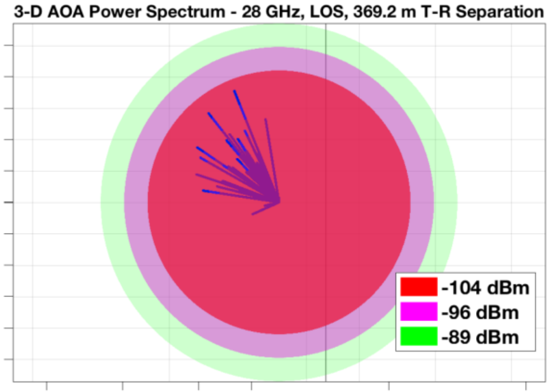
Allows for different individual antenna element types (e.g., patch antennas, vertical antennas, horns)

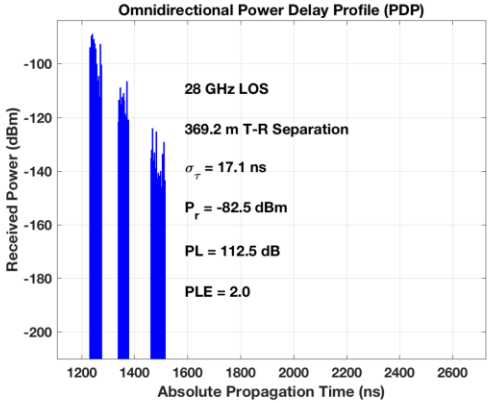
Avoids the trouble of dealing with myriad antenna fabrication and connection details needed to make an array

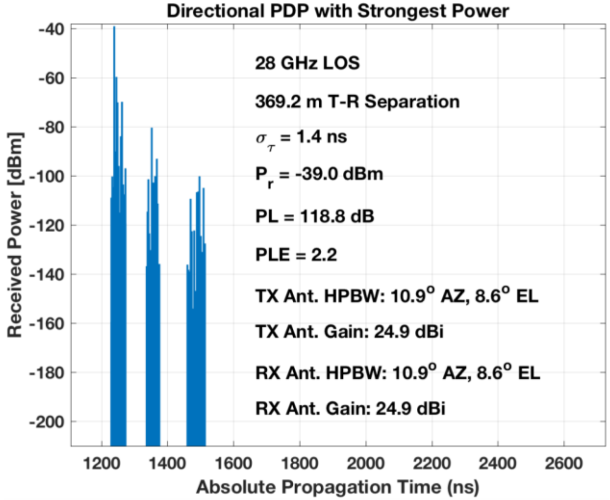
Provides users with the freedom to implement an array antenna pattern of their choice for system simulations

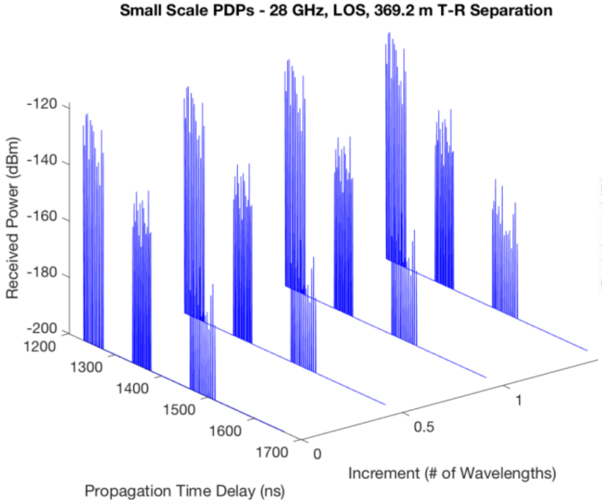
# Example Output Figure Files of NYUSIM

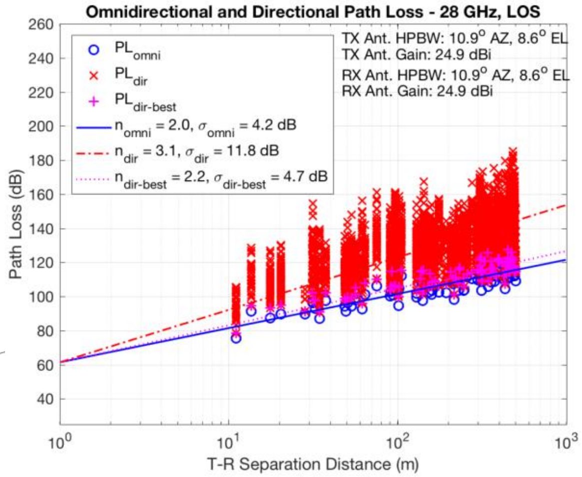


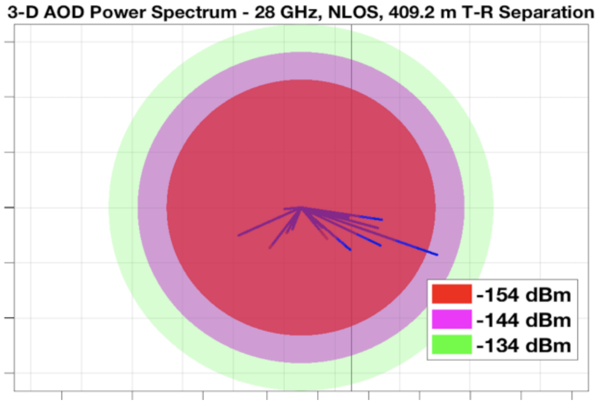



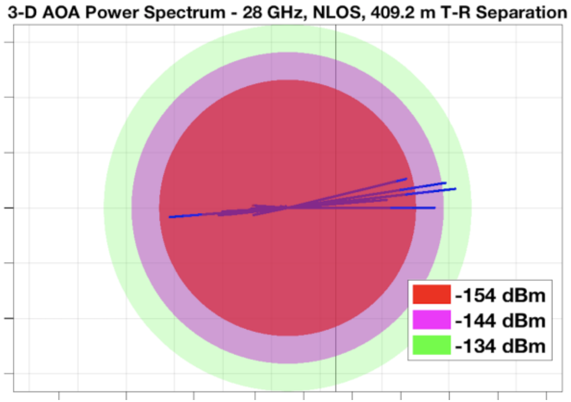



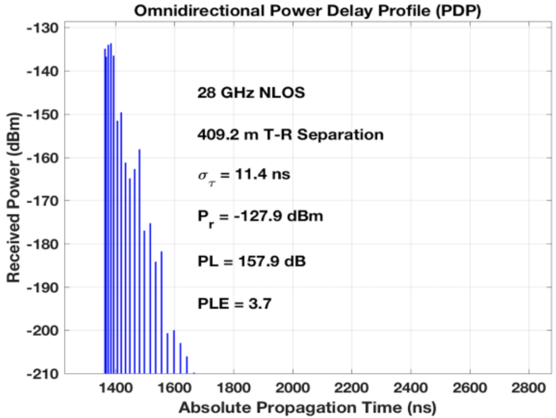



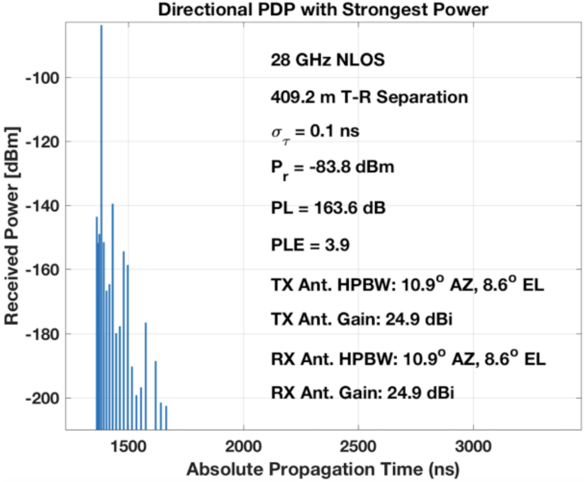



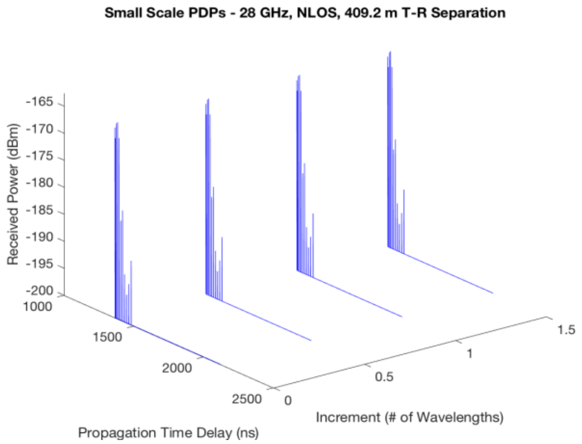
# Example Output Figure Files of NYUSIM

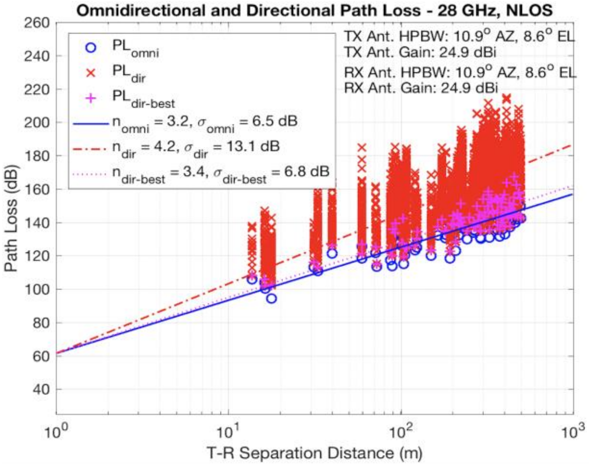


# Output Data Files of NYUSIM

Easy to use output data files in constructing MIMO channel matrices and analyzing MIMO channel performance, as shown in [1]

[1] T. S. Rappaport, S. Sun and M. Shafi, “5G channel model with improved accuracy and efficiency in mmWave bands,” in *IEEE 5G Tech Focus*, Mar. 2017.

AODLobePowerSpectrum: *N* sets of .txt files and *N* .mat files

AOALobePowerSpectrum: *N* sets of .txt files and *N* .mat files

OmniPDP: *N* .txt files and *N* .mat files

DirectionalPDP: *N* .txt files and *N* .mat files

SmallScalePDP: *N* .txt files and *N* .mat files

→ **Each of these files is associated with each of the five output figures per simulation run**

BasicParameters: one .txt file and one .mat file

OmniPDPInfo: one .txt file and one .mat file

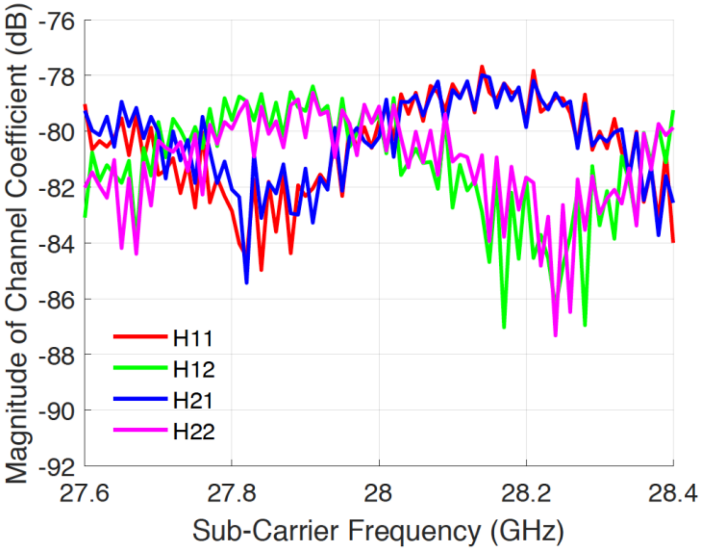
DirPDPInfo: one .txt file and one .mat file

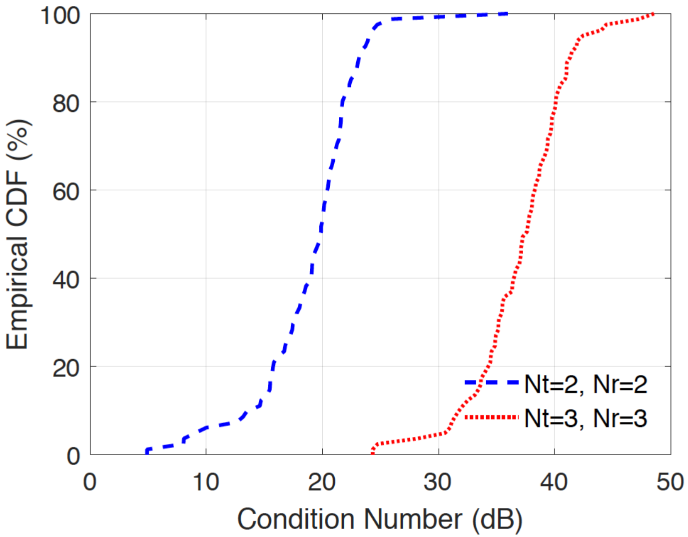
→ **Each of these files contains the common or collective parameters for all *N* continuous simulation runs**

# Applications of NYUSIM

5G New Radio (NR) OFDM waveform using 1600 sub-carriers within an 800 MHz RF bandwidth centered at 28 GHz

Using the output data files "BasicParameters.mat" and "DirPDPInfo.mat" generated from NYUSIM, key channel parameters such as path gain, delay, phase, AoD, AoA, etc., can be obtained and utilized to calculate MIMO OFDM channel coefficients and condition number

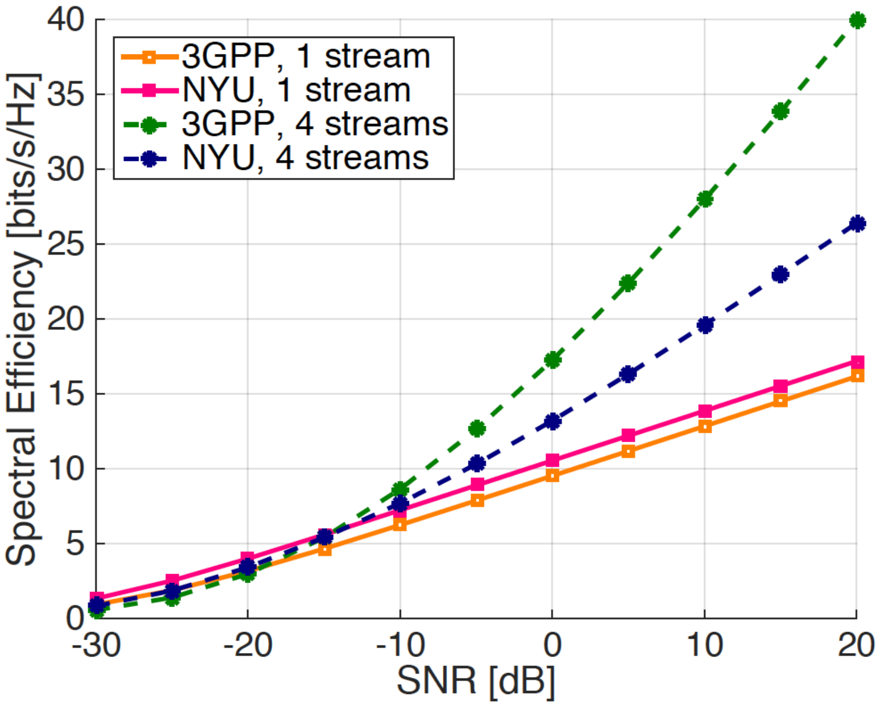



- Varying channel coefficients for different OFDM sub-carriers
- Worse channel condition (higher condition number) for 3x3 channels, due to limited rank in mmWave channels

# NYUSIM vs. 3GPP Channel Model

3GPP channel model [1]:
Grossly inaccurate for real-world measured data
Overestimates channel diversity (unrealistically large number of clusters for mmWave bands)




UMi street canyon scenario:
3GPP channel model: 12 clusters in LOS, 19 clusters in NLOS, 20 subpaths per cluster
NYUSIM channel model: up to 6 time clusters and 5 spatial lobes

3GPP channel model overestimates the diversity of mmWave channels [2]


[1] 3GPP, "Study on channel model for frequency spectrum above 6 GHz," 3rd Generation Partnership Project (3GPP), TR 38.900 V14.2.0, Dec. 2016. [Online]. Available: http://www.3gpp.org/DynaReport/38900.htm

[2] T. S. Rappaport, S. Sun, and M. Shafi, "5G channel model with improved accuracy and efficiency in mmWave bands," in *IEEE 5G Tech Focus*, vol. 1, no. 1, Mar. 2017.

# Conclusion

- An open-source channel simulator, **NYUSIM**, was developed based on **extensive field measurements at mmWave bands**, available at http://wireless.engineering.nyu.edu/nyusim

- NYUSIM recreates wideband PDPs/CIRs and channel statistics for a variety of carrier frequencies, RF bandwidths, antenna beamwidths, environment scenarios, and atmospheric conditions, based on measurement data over five years

- NYUSIM utilizes a realistic **3D** statistical spatial channel model, including **physically-based** path loss model and clustering approach, which can be used for 4G and 5G wireless for 0.5 – 100 GHz

- NYUSIM can be used widely, such as analyzing cell coverage and MIMO channel capacity

# NYU WIRELESS Industrial Affiliates

**Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF**

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# Questions