NYU WIRELESS

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Future Wireless Technologies: MmWave, THz, and beyond

Prof. Theodore S. Rappaport

MILLIMETER WAVE COALITION

SEPTEMBER 27, 2018

Circuits: Terahertz (THz) and Beyond

Special Seminar Series Co-sponsored by NYU WIRELESS — Fall 2018

Pioneering circuit designers explain how they are exploring the outer limits of engineering capabilities

"Silicon-based Integrated Sensors with On-chip Antennas: From THz Pulse Sources to Miniaturized Spectrometers," Aydin Babakhani, UCLA 9/5/18, 11:00am

"Terahertz Communications: From Nanomaterials to Ultra-broadband Networks," Josep Miquel Jornet, University at Buffalo 9/27/18, 11:00am

"Monolithic Phased Arrays: Radiofrequencies to Optical Frequencies," Hossein Hashemi, University of Southern California 10/3/18, 11:00am

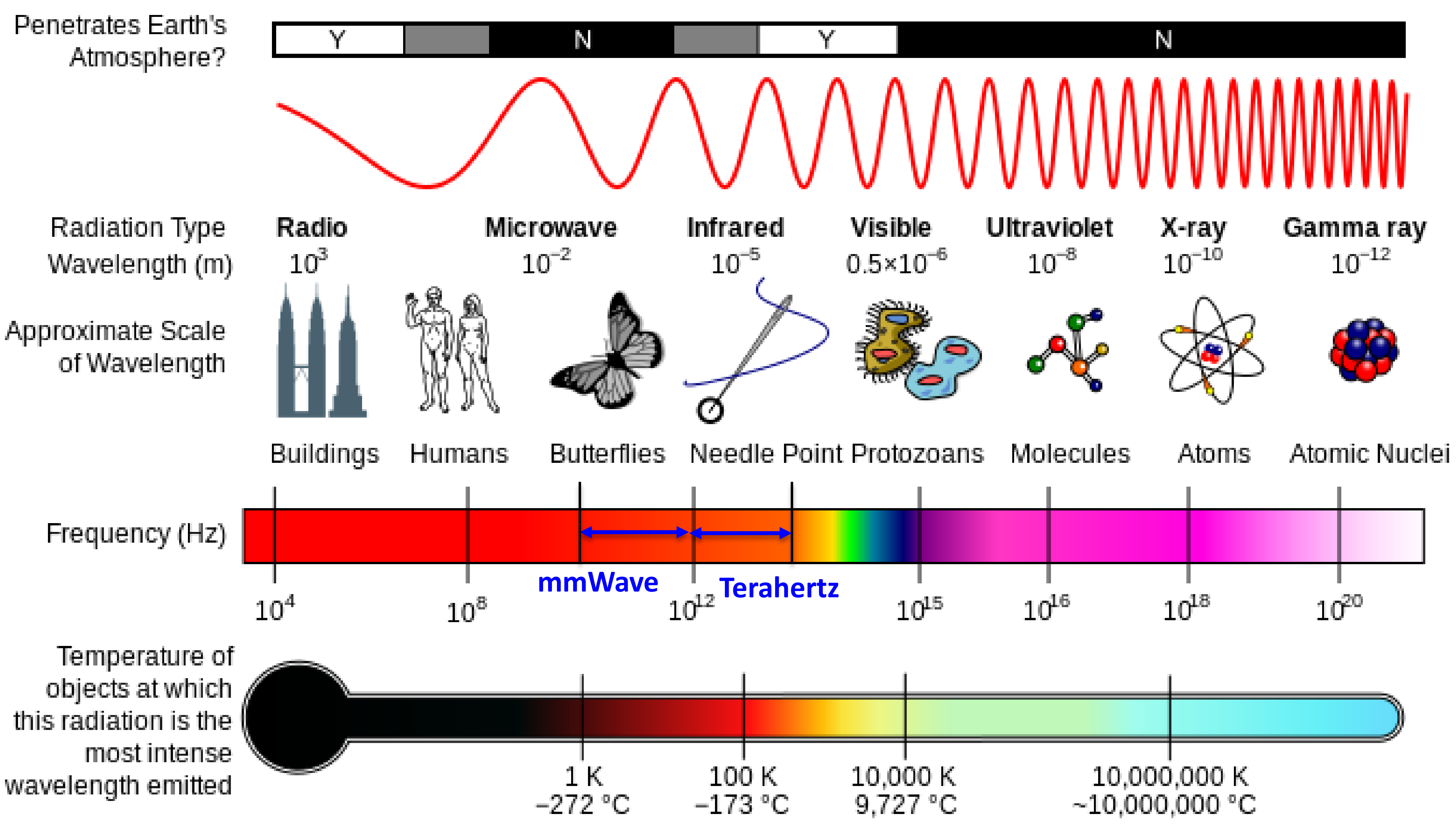
"Wireless above 100GHz," Mark Rodwell, UC Santa Barbara 10/11/18, 11:00am

"Enabling the Third Wireless Revolution through Transformative RF/mm-Wave Circuits, Wireless Systems and Sensing Paradigms," Harish Krishnaswamy, Columbia University 11/7/18, 11:00am

"Channel Characteristics for Terahertz Wireless Communications," Daniel M. Mittleman, Brown University 11/15/18, 11:00am

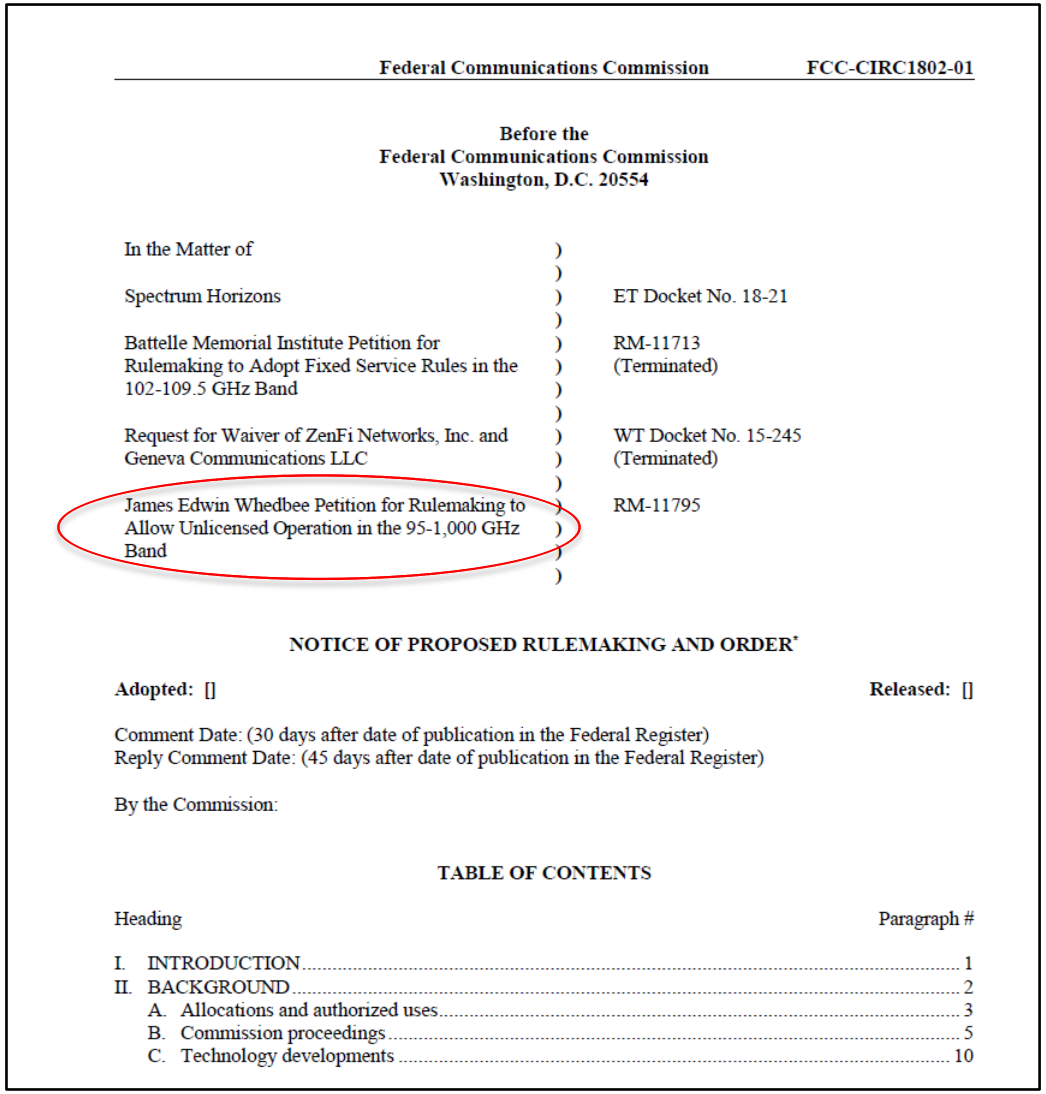
"Out of Many, Many: The Path towards Scalable, Integrated, mm-Wave MIMO Arrays," Arun Natarajan, Oregon State University, 12/6/18, 11:00am

Electromagnetic Spectrum



https://en.wikipedia.org/wiki/Electromagnetic_spectrum

FCC Proposes "Spectrum Horizons" > 95 GHz



Federal Communications Commission FCC-CIRC1802-01

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
Spectrum Horizons	)	ET Docket No. 18-21
Battelle Memorial Institute Petition for Rulemaking to Adopt Fixed Service Rules in the 102-109.5 GHz Band	)	RM-11713 (Terminated)
Request for Waiver of ZenFi Networks, Inc. and Geneva Communications LLC	)	WT Docket No. 15-245 (Terminated)
James Edwin Whedbee Petition for Rulemaking to Allow Unlicensed Operation in the 95-1,000 GHz Band	)	RM-11795

NOTICE OF PROPOSED RULEMAKING AND ORDER*

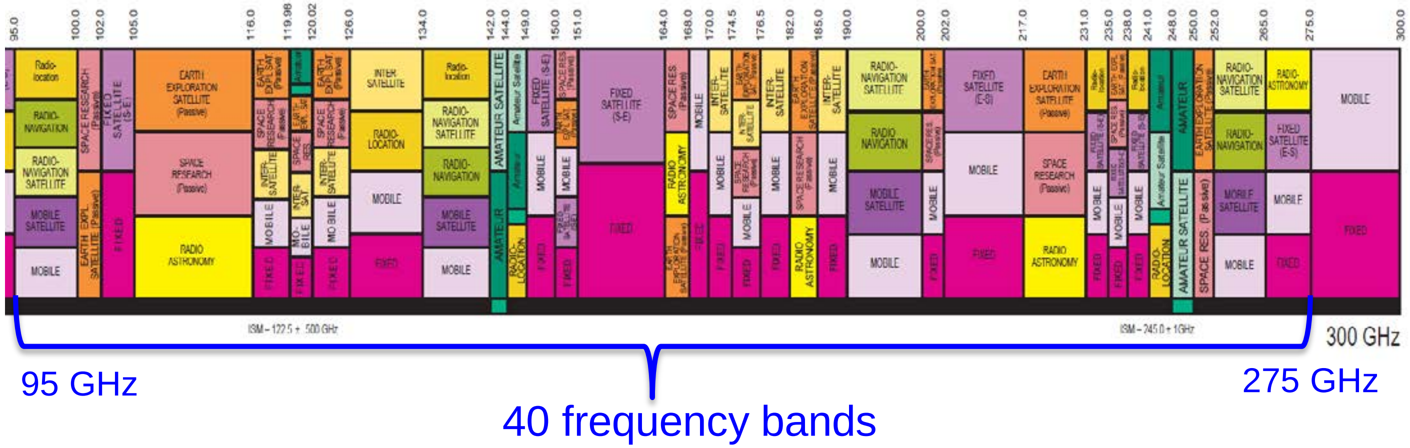
Adopted: [] **Released:** []

Comment Date: (30 days after date of publication in the Federal Register)
Reply Comment Date: (45 days after date of publication in the Federal Register)

By the Commission:

TABLE OF CONTENTS

Heading Paragraph #



- February 22, 2018—FCC initiated a proceeding to expand access to spectrum **above 95 GHz**.
- Seeks comment on making a total **102.2 GHz** of spectrum available for **licensed** point-to-point services, **15.2 GHz** of spectrum for use by **unlicensed** devices.
- Seeks comment on creating a new category of **experimental licenses** available in spectrum **between 95 GHz and 3 THz**.
- **NYU** is one of the chosen universities to help FCC to create the **Experimental License System**.

https://apps.fcc.gov/edocs_public/attachmatch/DOC-348982A1.pdf

mmWave Coalition

Frequencies above 95 GHz are seriously under-developed in the U.S. due to lack of an adequate regulatory framework for their use. http://mmwavecoalition.org/

The mmWave Coalition is a group advocating for the FCC to open several large contiguous blocks of spectrum from 95-275 GHz

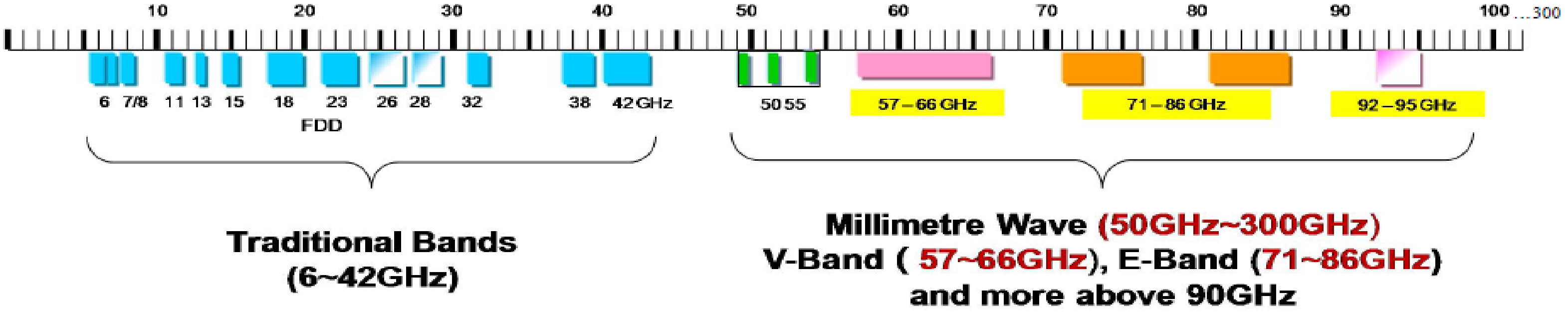
The mmWave Coalition is proposing rules for commercialization of fixed and mobile systems above 95 GHz with the goal of creating a global ecosystem for these systems

Current members are Nokia, ACB Inc., Nuvotronics, Keysight, Virginia Diodes, RaySecur, Azbil, Global Foundries, Qorvo, NYU.

Annual Contribution is $5k for a large company, $100 for an Academic Institution, and $1.5k for others. Each member can nominate one person to act as its “Principal” representing it on the Steering Committee (currently chaired by Nokia).

Other Activities on Spectrum Above 95 GHz

- **Europe**: ETSI ISG mWT is to propose the wireless transmission applications and use cases that can be addressed by millimeter wave spectrum, focusing on frequency bands from 50 GHz up to 300 GHz.

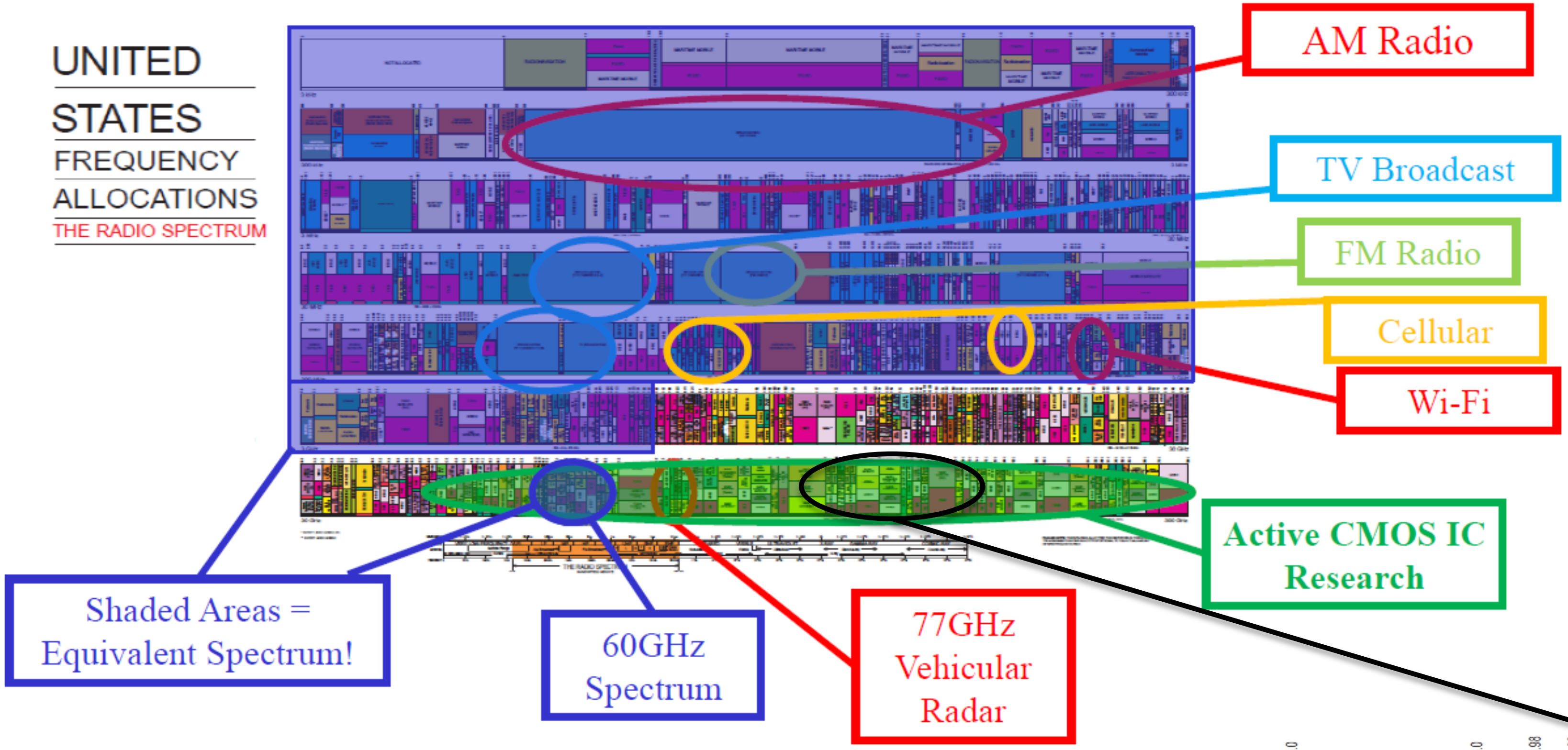


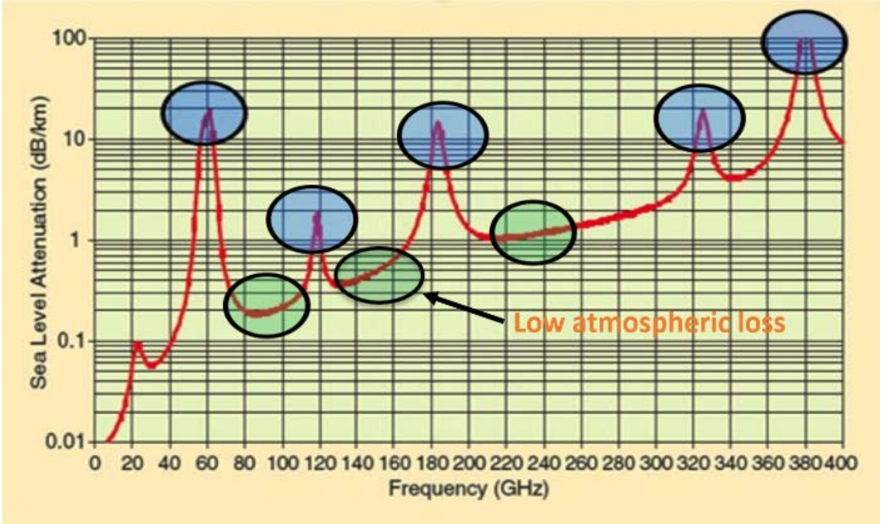
- **ITU-R**: WRC-19 Agenda Item 1.15 will consider identification of frequency bands for use by administrations for the land-mobile and fixed services applications operating in the frequency range 275–450 GHz, in accordance with Resolution 767 (WRC-15).

Asia-Pacific Telecommunity (APT) 275–1000 GHz → WRC-15

European Conference of Postal and Telecommunications Administrations (CEPT) 275-1000 GHz → WRC-15

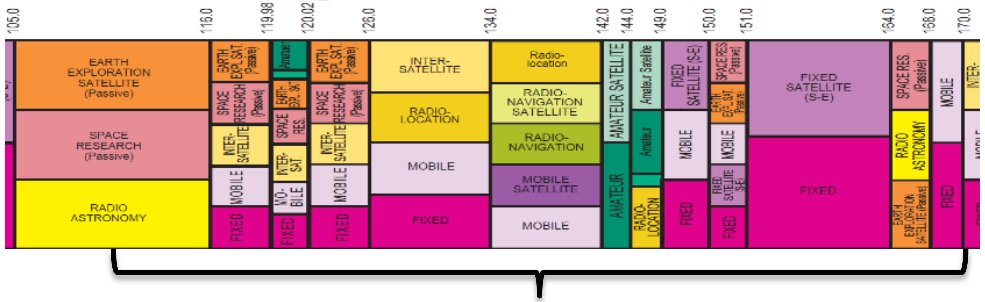
Moving up to D-band (110-170 GHz)





The atmospheric absorption at 140 GHz is less than 1 dB/km [2]!

Spectrum: Key to Wireless Capacity [1]



D-band 110-170 GHz

[1] T. S. Rappaport, et. al., Millimeter Wave Wireless Communications, Pearson/Prentice Hall, c. 2015
[2] [1] T. S. Rappaport, J. N. Murdock and F. Gutierrez, "State of the Art in 60-GHz Integrated Circuits and Systems for Wireless Communications," in Proceedings of the IEEE, vol. 99, no. 8, pp. 1390-1436, Aug. 2011.

Published Data on Worldwide mmWave/THz System Experiments

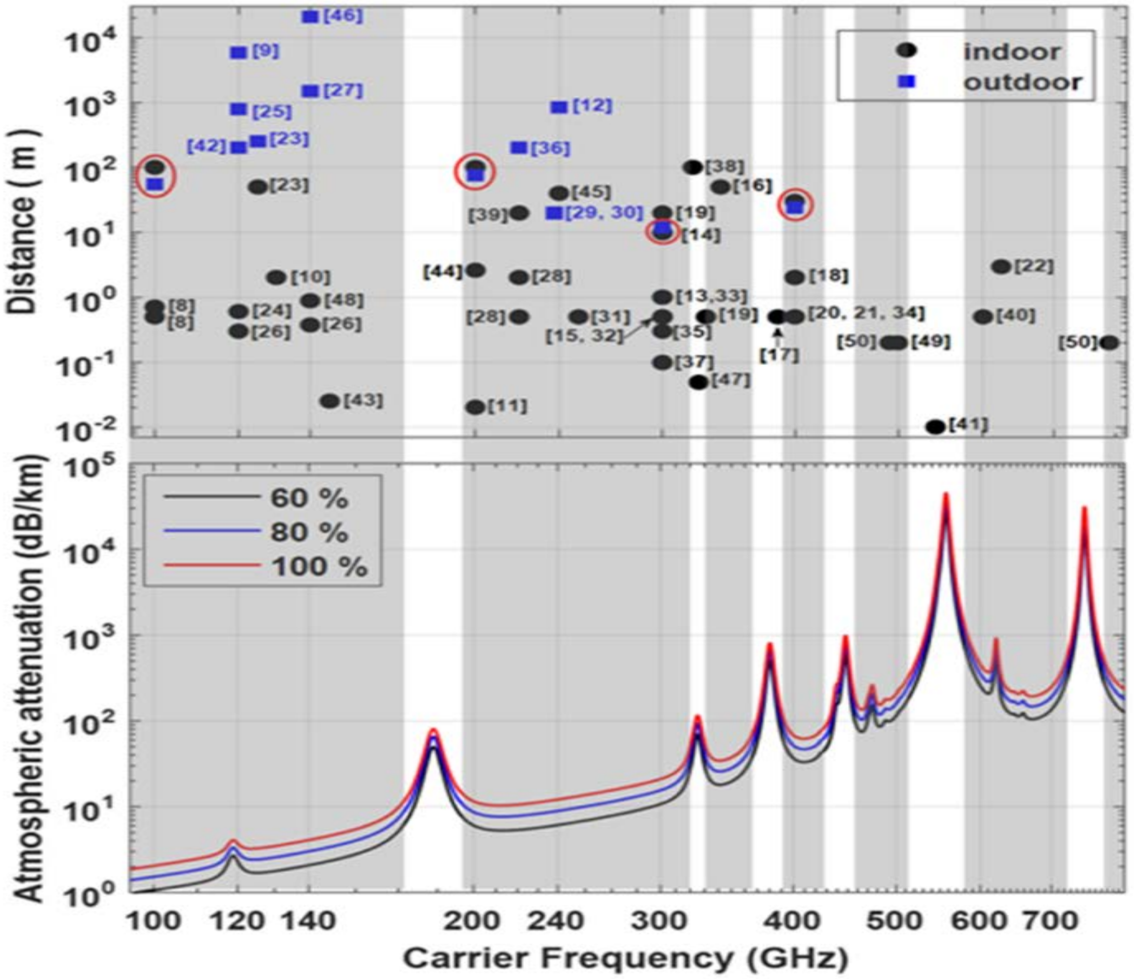


Fig. 1 Propagation Distance and Atmospheric Attenuation vs. Carrier Frequency above 100 GHz [1].

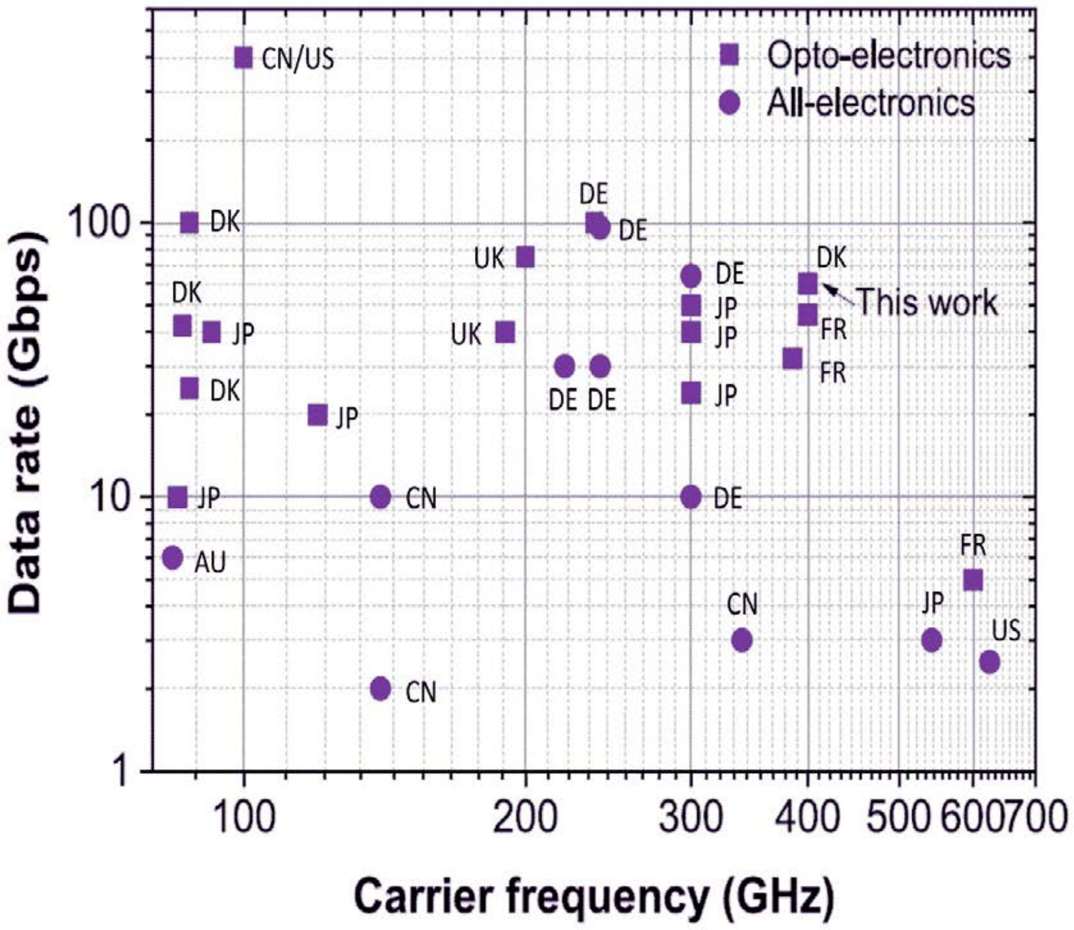
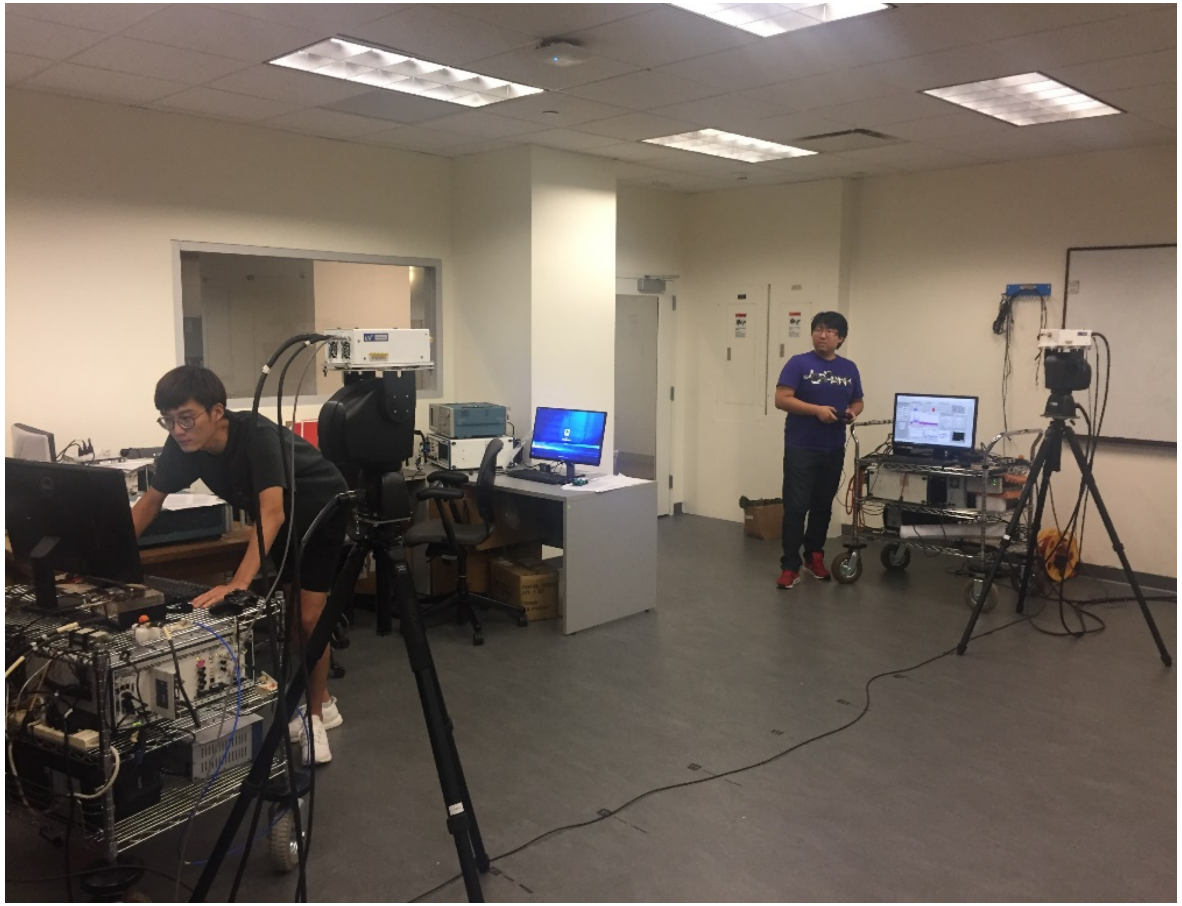


Fig. 2 Achievable Data Rate vs. Carrier Frequency above 100 GHz [2].

[1] J. Ma, R. Shrestha, L. Moeller, and D. M. Mittleman, "Channel performance for indoor and outdoor terahertz wireless links," APL Photonics, vol. 3, no. 5, pp. 1–13, Feb. 2018.
[2] Yu, Asif, et al., "400-GHz Wireless Transmission of 60-Gb/s Nyquist-QPSK Signals Using UTC-PD and Heterodyne Mixer," IEEE Transactions on Terahertz Science and Technology, Issue No. 99, p. 1-6 (August 2016)

140 GHz Broadband Channel Sounder at NYU WIRELESS

Students are conducting measurements with the 140 GHz channel sounder system [1]



140 GHz broadband channel sounder demo at Brooklyn 5G Summit [2]

[1] Y. Xing and T. S. Rappaport, “Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz,” IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

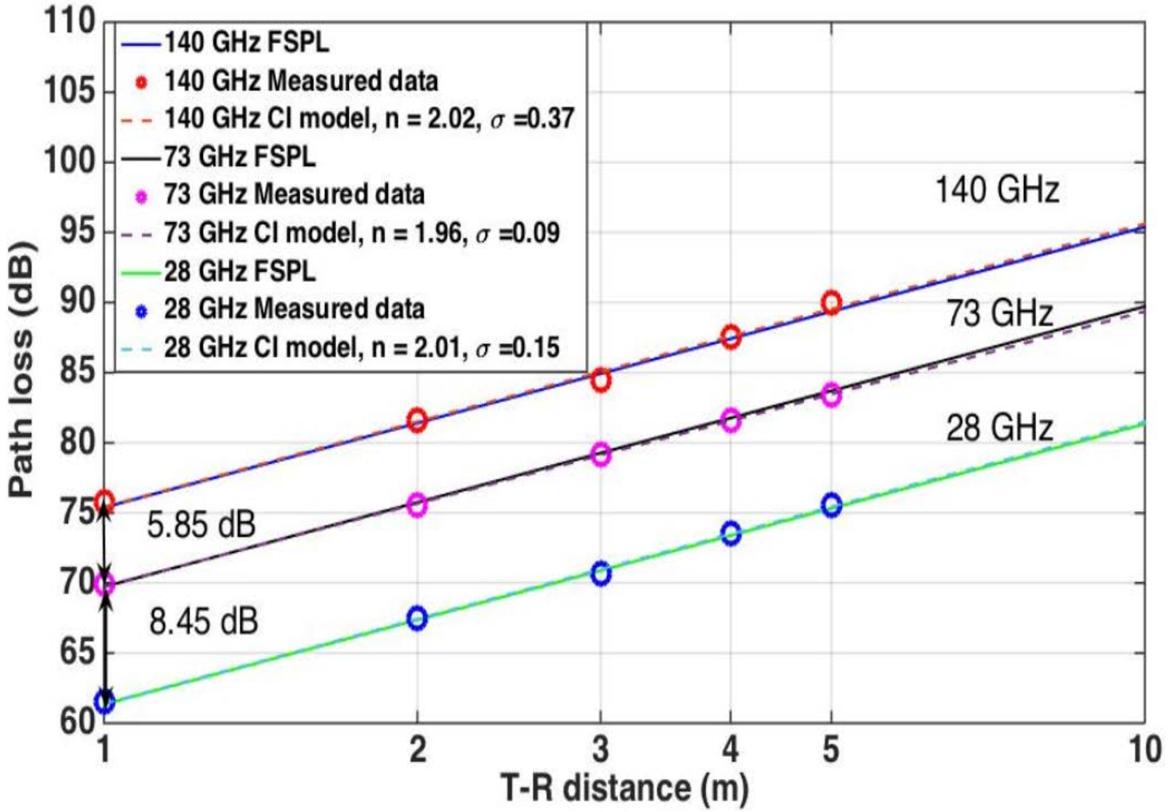
[2] https://ieeetv.ieee.org/event-showcase/brooklyn5g2018

NYU WIRELESS 140 GHz Channel Sounder and Free Space Path Loss at 28, 73, 140 GHz

NYU 140 GHz Channel Sounder System [1]

Description	Specification
LO Frequency	22.5 GHz ×6 = 135 GHz
IF Frequency	5-9 GHz (4 GHz bandwidth)
RF Frequency	140-144 GHz
Upconverter IF input	-5 dBm typically 10 dBm (damage limit)
Downconverter RF input	-15 dBm typically 0 dBm (damage limit)
TX output power	0 dBm
Antenna Gain	25 dBi / 27 dBi
Antenna HPBW	10º / 8º
Antenna Polarization	Vertical / Horizontal

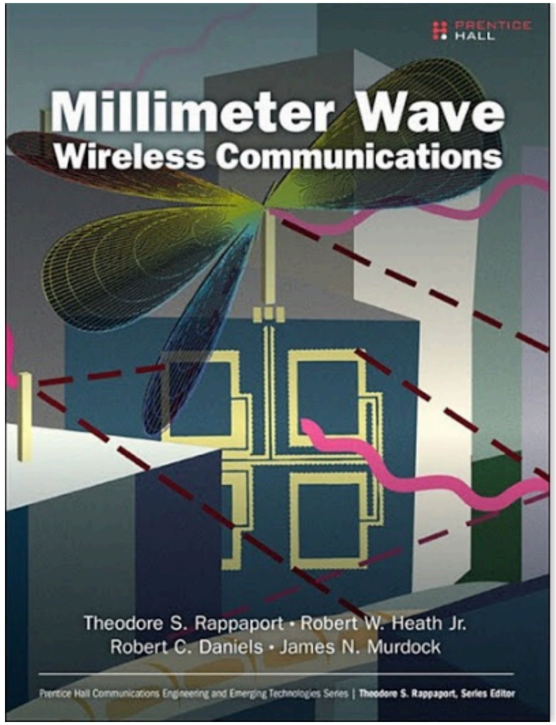
FSPL verifications following the proposed method
at 28, 73, and 140 GHz [2] (after removing antenna gains)



As expected, FSPL at 140/73/28 GHz follows the Laws of Physics and satisfies Friis' equations with antenna gains removed.

[1] Y. Xing and T. S. Rappaport, "Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz," IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.
[2] Y. Xing, O. Kanhere, S. Ju, T. S. Rappaport, G. R. MacCartney Jr., "Verification and calibration of antenna cross-polarization discrimination and penetration loss for millimeter wave communications," 2018 IEEE 88th Vehicular Technology Conference, Aug. 2018, pp. 1–6.

Received Power vs. Carrier Frequency



- Friis free space equation: $P_r(\mathrm{d}) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$

- Antenna Gain: $G = \frac{4\pi A_e}{\lambda^2}$,
- A_e : effective aperture

- Speed of light: $c = f\lambda$

- Taking G_t and G_r into *Pr(d)*: $P_r(\mathrm{d}) = \frac{P_t \frac{4\pi A_{et}}{\lambda^2} \frac{4\pi A_{er}}{\lambda^2} \lambda^2}{(4\pi)^2 d^2}$

$$= \frac{P_t A_{et} A_{er}}{d^2 \lambda^2} = \frac{P_t A_{et} A_{er} f^2}{d^2 c^2}$$

Keep A_e constant at both TX and RX, increasing carrier frequency *f*, *λ* decreases, *G* increases!
So *Pr (d) actually increases* quadratically with *f* [Rap15a, Ch.3, Page 104]!

[Rap15a] T. S. Rappaport, et. al., "Millimeter Wave Wireless Communications," Pearson/Prentice Hall c. 2015.

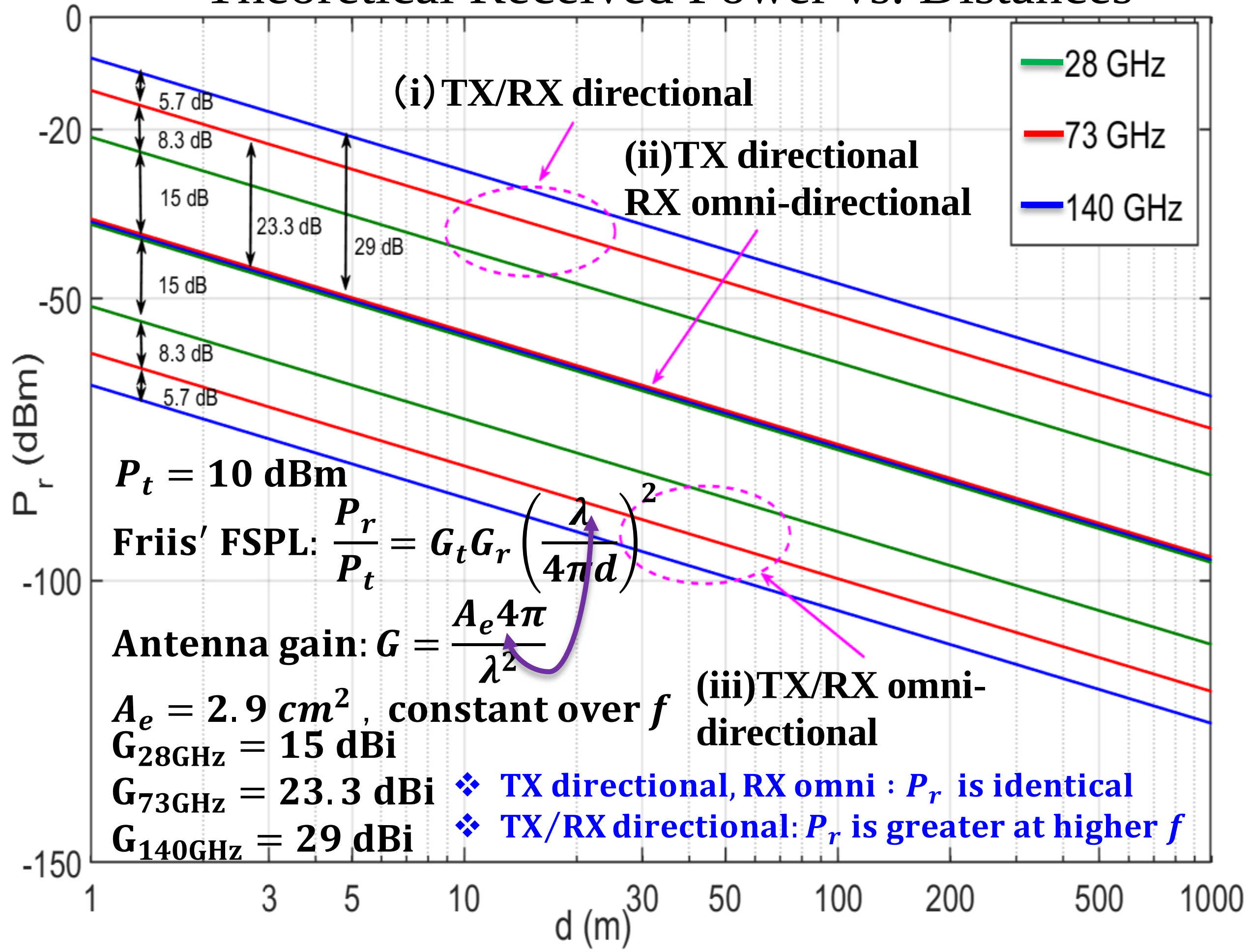
- Noise: N= kT_0B.

With high gain directional antennas, higher frequency allows more bandwidth for the same SNR!

Power Levels and Penetration Loss Following the Proposed Methods at 28, 73, and 140 GHz

NYU TANDON SCHOOL OF ENGINEERING — NYU WIRELESS

Theoretical Received Power vs. Distances



DIRECTIONAL ANTENNAS WITH EQUAL APERTURE HAVE MUCH LESS PATH LOSS AT HIGHER FERQUENCIES ([1] Ch.3 Page 104) !!!

Penetration Loss at 28, 73, and 140 GHz

Frequency (GHz)	Material Under Test	Thickness (cm)	Penetration Loss (dB)
28	Clear glass No.1	1.2	3.60
	Clear glass No.2	1.2	3.90
	Drywall No.1	38.1	6.80
73	Clear glass No.3	0.6	7.70
	Clear glass No.4	0.6	7.10
	Drywall No.2	14.5	10.06
140	Clear glass No.3	0.6	8.24
	Clear glass No.4	0.6	9.07
	Drywall No.2	14.5	15.02
	Glass door	1.3	16.20
	Drywall with Whiteboard	17.1	16.69

PENETRATION LOSS INCREASES WITH FREQUENCY BUT THE AMOUNT OF LOSS IS DEPENDENT ON THE MATERIAL [2]

[1] T. S. Rappaport, et. al., "Millimeter Wave Wireless Communications," Pearson/Prentice Hall c. 2015.
[2] Y. Xing and T. S. Rappaport, "Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz," IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

XPD and Penetration Loss Measurements Guidelines [1]

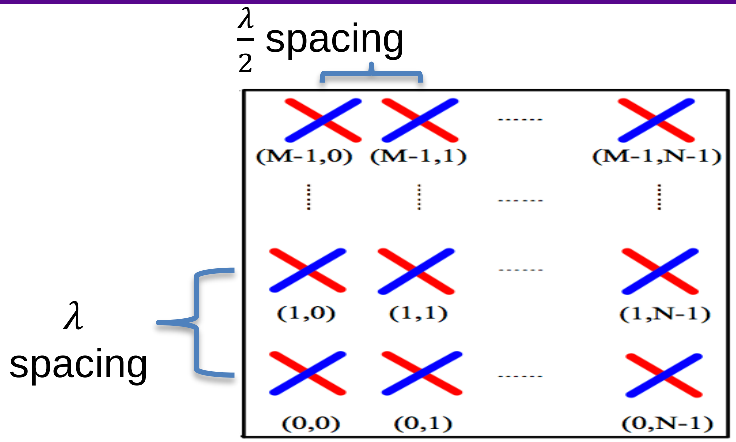
- Antenna cross polarization Discrimination (XPD) and penetration loss are vital for 5G mmWave communication

- Different research groups using different methods may cause errors (e.g., scattering effects, multipath)

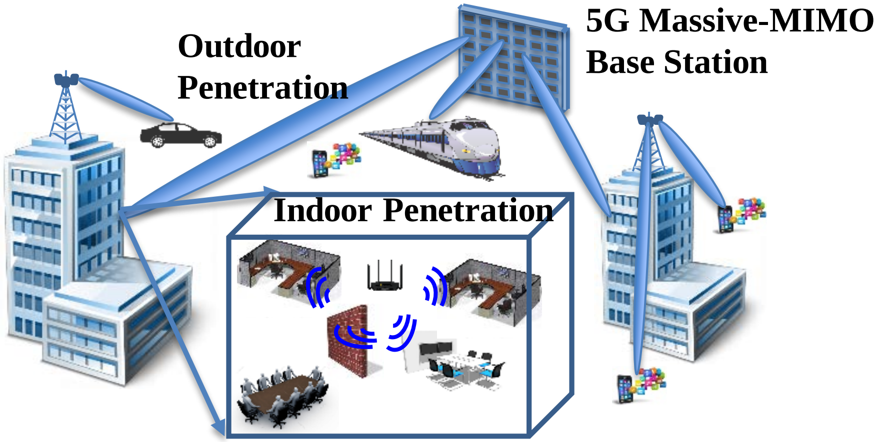
- Proposal: standardized measurement guidelines and verification procedures for XPD and penetration loss measurements

- The proposed methods ensure accurate XPD and penetration loss measurements by any party at any frequency/bandwidth

- XPD and penetration loss measurements and results at 73 GHz using the proposed methods.



(a) Dual-polarized antenna array [2]



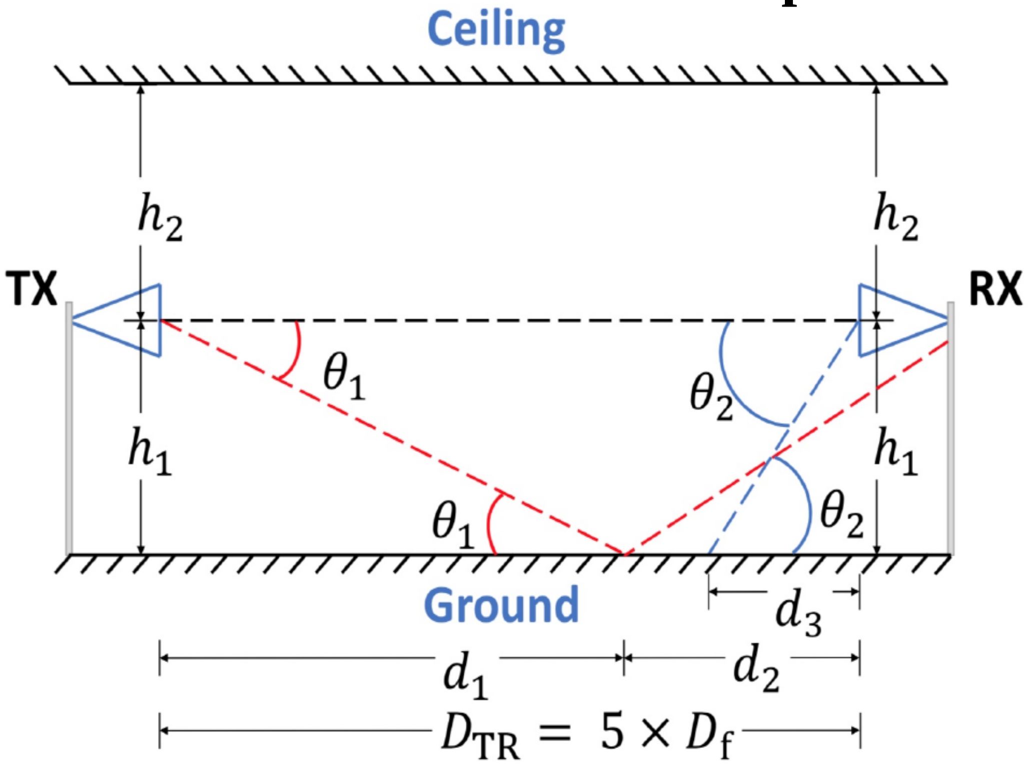
(b) Penetration in 5G mmWave communications

[1] Y. Xing, O. Kanhere, S. Ju, T. S. Rappaport, G. R. MacCartney Jr., “Verification and calibration of antenna cross-polarization discrimination and penetration loss for millimeter wave communications,” 2018 IEEE 88th Vehicular Technology Conference, Aug. 2018, pp. 1–6.

[2] S. Sun, T. S. Rappaport, and M. Shafi, ”Hybrid beamforming for 5G millimeter-wave multi-cell networks,” in Proceedings of the IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Honolulu, HI, USA, Apr. 2018.

Standardized Verification Approaches to XPD and Penetration Loss Measurements

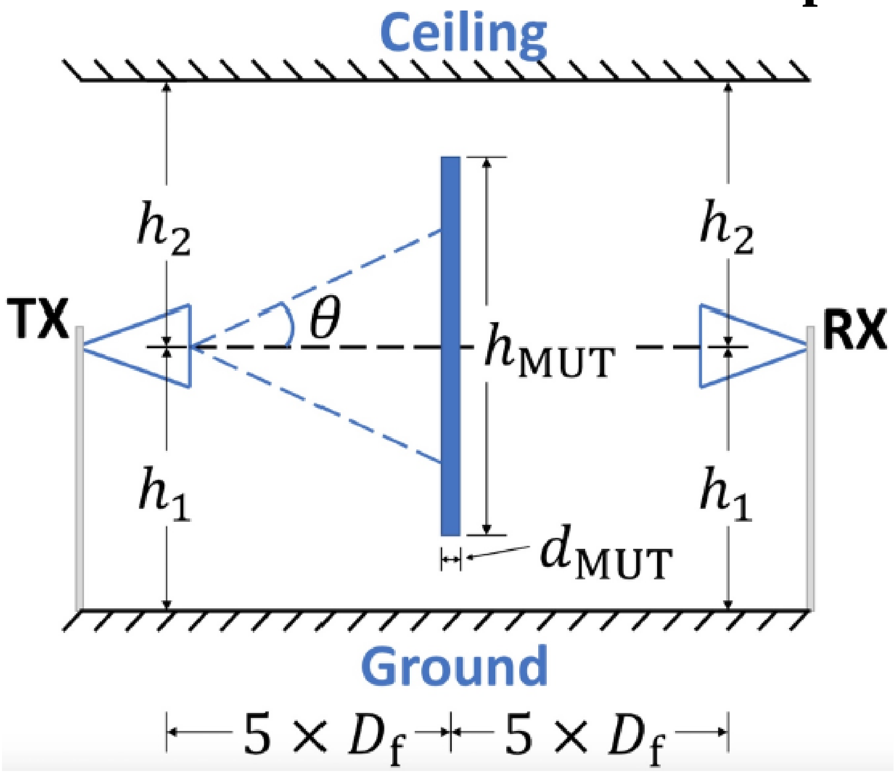
XPD Measurement Setups



$$D_f = \frac{2D^2}{\lambda} \qquad D_{TR} \geqslant 5 \times D_f$$

$$h_1, h_2 > 2 \times \left(\frac{D_{TR}}{\left(\frac{1}{\tan(\theta_1)}\right) + \left(\frac{1}{\tan(\theta_2)}\right)} \right)$$

Penetration Loss Measurement Setups



$$h_{MUT} >> 5 \times 2 \times D_f \cdot \tan\left(\frac{HPBW}{2}\right)$$

$$h_1, h_2 > 2 \times \left(\frac{D_{TR}}{\left(\frac{1}{\tan(\theta_1)}\right) + \left(\frac{1}{\tan(\theta_2)}\right)} \right)$$

XPD Measurements and Results at 73 GHz

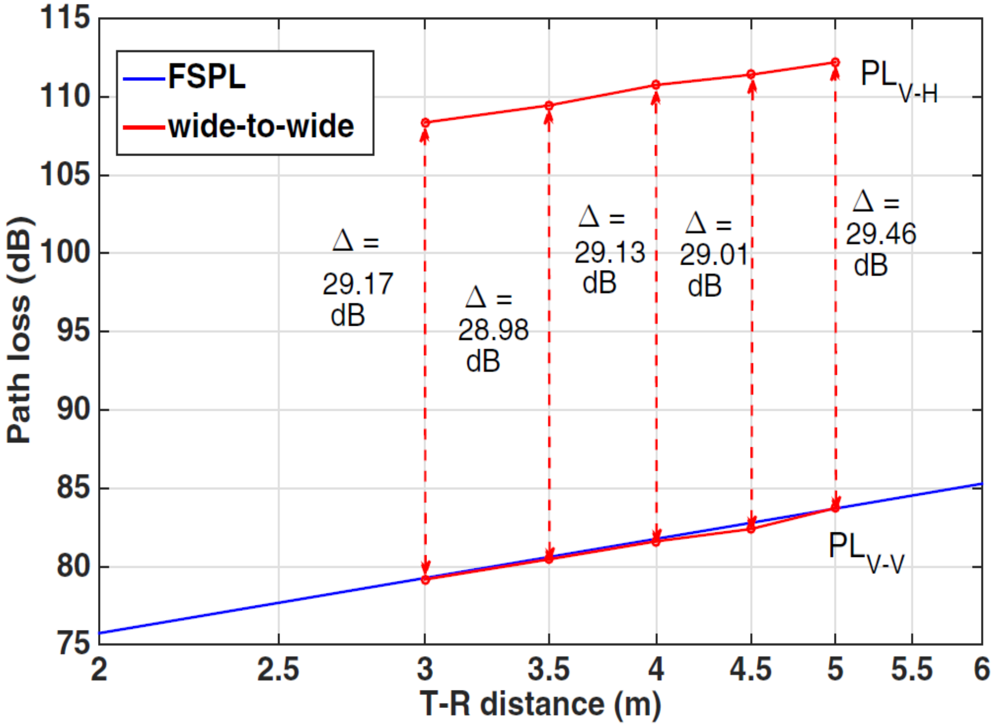
TABLE I: XPD Measurement Results at 73 GHz

	3 m	3.5 m	4 m	4.5 m	5 m	Mean	σ
Wide-to-Wide XPD	29.17 dB	28.98 dB	29.13 dB	29.01 dB	29.46 dB	29.15 dB	0.19 dB
Narrow-to-Wide XPD	28.73 dB	28.98 dB	29.58 dB	29.42 dB	29.79 dB	29.30 dB	0.44 dB
Narrow-to-Narrow XPD	28.54 dB	30.60 dB	30.17 dB	30.9 dB	31.31 dB	30.30 dB	1.07 dB

$$PL_{\text{V-V}}(d)(\text{dB}) = P_{\text{t-V}}(\text{dBm}) - P_{\text{r-V}}(d)(\text{dBm}) + G_{\text{TX}}(\text{dBi}) + G_{\text{RX}}(\text{dBi}),$$

$$PL_{\text{V-H}}(d)(\text{dB}) = P_{\text{t-V}}(\text{dBm}) - P_{\text{r-H}}(d)(\text{dBm}) + G_{\text{TX}}(\text{dBi}) + G_{\text{RX}}(\text{dBi}),$$

$$XPD(d)(\text{dB}) = PL_{\text{V-H}}(d)(\text{dB}) - PL_{\text{V-V}}(d)(\text{dB}),$$



- XPD values are constant over relatively closely separated distances.
- Different antenna combinations only induce slight variance to the XPD values.

[1] Y. Xing, O. Kanhere, S. Ju, T. S. Rappaport, G. R. MacCartney Jr., "Verification and calibration of antenna cross-polarization discrimination and penetration loss for millimeter wave communications," 2018 IEEE 88th Vehicular Technology Conference, Aug. 2018, pp. 1–6.

Penetration Loss Measurements and Results at 73 GHz

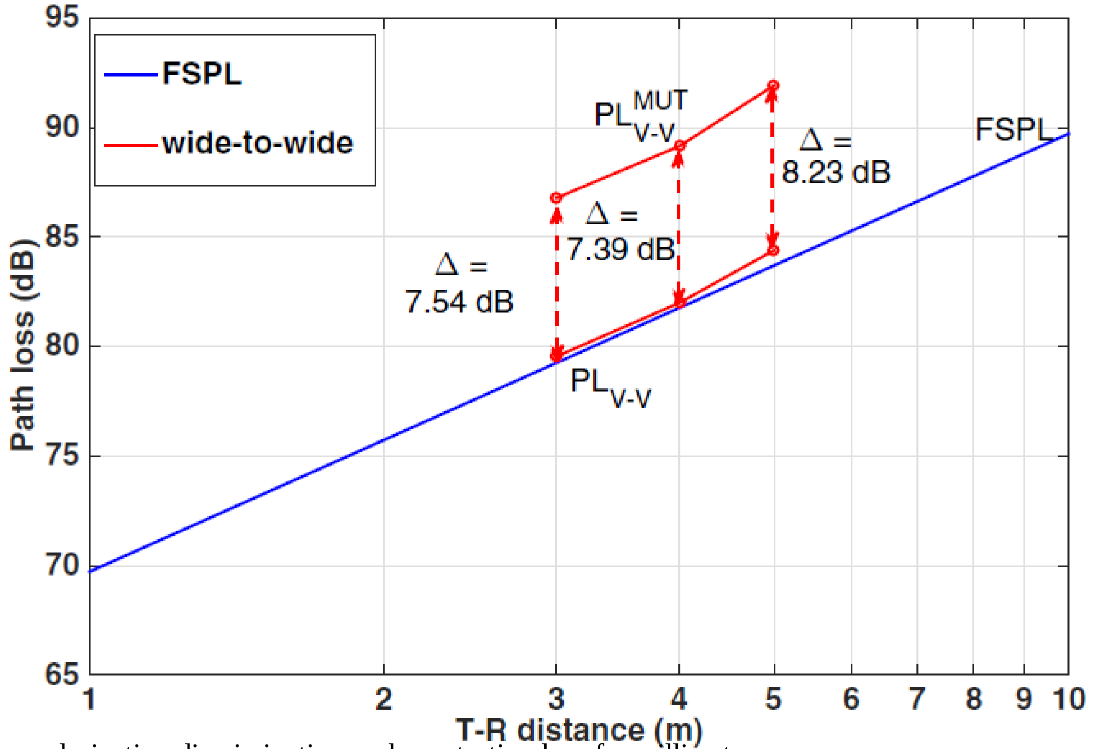
TABLE II: Penetration Loss Measurement Results at 73 GHz

MUT Clear Glass (1.2 cm thickness)	**3 m**	**4 m**	**5m**	**Mean**	σ
V-V	7.54 dB (6.28 dB/cm)	7.39 dB (6.15 dB/cm)	8.23 dB (6.86 dB/cm)	7.72 dB (6.43 dB/cm)	0.45 dB
V-H	8.48 dB (7.06 dB/cm)	7.16 dB (5.96 dB/cm)	7.62 dB (6.35 dB/cm)	7.75 dB (6.46 dB/cm)	0.67 dB

$$L_{V-V}[\text{dB}] = P_t[\text{dBm}] - P_{r-V}^{MUT}(d)[\text{dBm}] + G_{TX}[\text{dBi}] + G_{RX}[\text{dBi}] - PL_{V-V}(d)[\text{dB}],$$

$$L_{V-H}[\text{dB}] = P_t[\text{dBm}] - P_{r-H}^{MUT}(d)[\text{dBm}] + G_{TX}[\text{dBi}] + G_{RX}[\text{dBi}] - PL_{V-H}(d)[\text{dB}] - XPD[\text{dB}],$$

- Penetration loss of a 1.2 cm thick clear glass is 7.7 dB at 73 GHz.
- Penetration loss is constant over T-R separation distances [1].



[1] Y. Xing, O. Kanhere, S. Ju, T. S. Rappaport, G. R. MacCartney Jr., "Verification and calibration of antenna cross-polarization discrimination and penetration loss for millimeter wave communications," 2018 IEEE 88th Vehicular Technology Conference, Aug. 2018, pp. 1–6.
[2] Y. Xing and T. S. Rappaport, "Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz," IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

THz Imaging

Tremendous progress in terahertz (THz) imaging since mid-1990's

- Advances in femtosecond optoelectronics in the late 1980's and early 1990's
- THz time-domain spectroscopy (THz-TDS)
- Both active and passive imaging

Advantages of THz imaging

- Superior spatial resolution due to the short wavelength
- Complementary information to microwaves, infrared, visible, ultraviolet, or x-ray imaging
- Material identification (molecular crystals possess vibrational absorption bands in the THz range)

Disadvantages of THz imaging

- Relatively long acquisition time
- Hard to find the focal plane
- Both active and passive imaging

[1] P. R. Smith, D. H. Auston, and M. C. Nuss, "Subpicosecond photoconducting dipole antennas," IEEE J.Quantum Electron. 24(2), 255–260 (1988).
[2] B. B. Hu and M. C. Nuss, "Imaging with terahertz waves," Opt. Lett. 20(16), 1716–1719 (1995).
[3] Daniel M. Mittleman, "Twenty years of terahertz imaging [Invited]," Opt. Express 26, 9417-9431 (2018)
[4] H. Zhong, A. Redo-Sanchez, and X.-C. Zhang, "Identification and classification of chemicals using terahertz reflective spectroscopic focal-plane imaging system," Opt. Express 14(20), 9130–9141 (2006).

Medical Imaging (1/2)

- **Low per-photon energy – no ionization hazard**

- **Submillimeter-wavelength - cell size is less than the wavelength.**
  - THz signals pass through tissue with only Tyndall scattering (proportional to f^2) rather than much stronger Rayleigh scattering (proportional to f^4) [1]

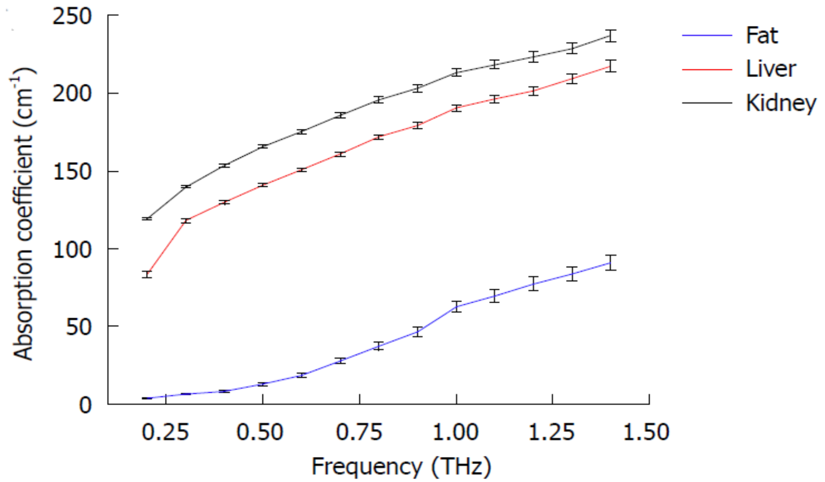
- **THz time-domain spectroscopy with coherent detection**
  - Both the phase and amplitude of the spectral components of the pulse are determined - absorption coefficients and spectral refractive indices easily measurable [2]

[1] Siegel, P.H., 2004. Terahertz technology in biology and medicine. *IEEE transactions on microwave theory and techniques*, *52*(10), pp.2438-2447.
[2] Dorney, T.D., Baraniuk, R.G. and Mittleman, D.M., 2001. Material parameter estimation with terahertz time-domain spectroscopy. *JOSA A*, *18*(7), pp.1562-1571.

Medical Imaging (2/2)

- **Tissue Characterization**
  - High absorption in polar liquids
  - Fatty tissue have fewer polar molecules, the absorption coefficient and refractive index of the fatty tissue are much lowe that those of the kidney and liver tissues. [1]

- **Cancer Detection**
  - Absorption coefficient and refractive index higher for tissue that contained tumors [1]



Mean absorption coefficients of kidney, liver and abdominal fat [1]

[1] Y. Sun, M. Y. Sy, Y.-X. J. Wang, A. T. Ahuja, Y.-T. Zhang, and E. Pickwell-Macpherson, "A promising diagnostic method: Terahertz pulsed imaging and spectroscopy," World J. Radio. 3(3), 55–65 (2011).

Applications of Indoor Positioning

- Guided museum tours [6]
- Navigation in large malls or office spaces [7]
- See-in-the-dark capabilities for firefighters and law enforcement
- IoT device and personnel tracking [8]
- Accurate positioning of equipment for automation in smart factories [9],[10]

[6] K. W. Kolodziej and J. Hjelm, Local Positioning Systems: LBS Applications and Services. CRC Press, May 2006.
[7] A. Puikkonen et al., “Towards designing better maps for indoor navigation: Experiences from a case study,” in 8th International Conference on Mobile and Ubiquitous Multimedia, Nov. 2009, pp. 16:1–16:4.
[8] L. Zhang, J. Liu, and H. Jiang, “Energy-efficient location tracking with smartphones for IoT,” in 2012 IEEE Sensors, Oct. 2012, pp. 1–4.
[9] T. S. Rappaport, “Indoor radio communications for factories of the future,” IEEE Commun. Magazine, vol. 27, no. 5, pp. 15–24, May 1989.
[10] S. Lu, C. Xu, R. Y. Zhong, and L. Wang, “A RFID-enabled positioning system in automated guided vehicle for smart factories,” Journal of Manufacturing Systems, vol. 44, pp. 179 – 190, July 2017.

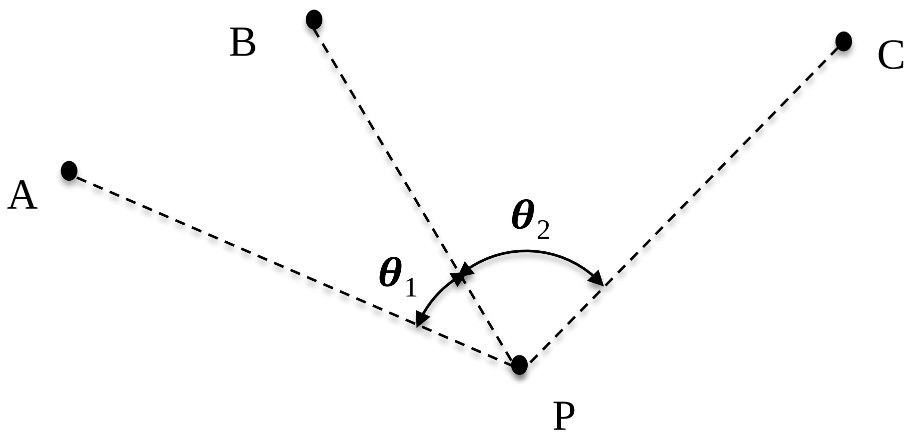
Indoor Positioning (2/2)

Advantages of operating at mmWave and THz frequencies

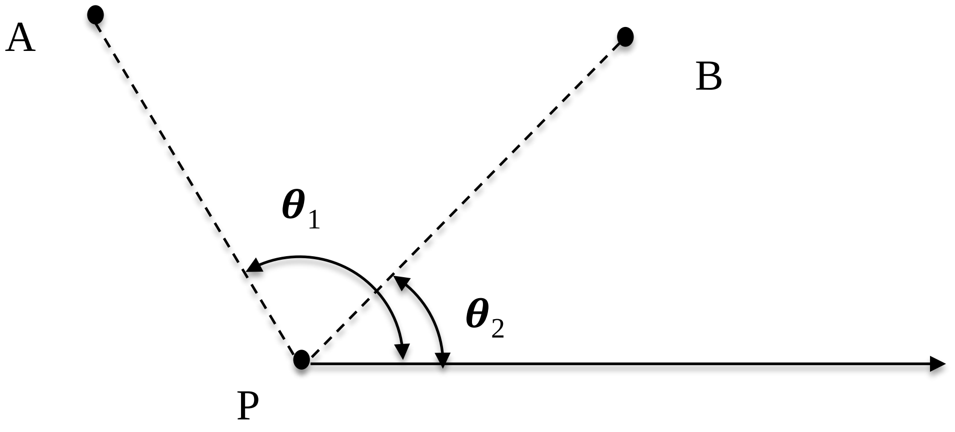
- Wide bandwidths enable fine resolution of multipath components, leading to accurate estimation of the time of arrival (ToA) of signals
- Sparse channels, narrow beam antennas ensure AoA estimated accurately
- Positioning can be added as a "feature" to pre-deployed wireless access points or base stations

AoA-Based Positioning

- RX position determined to be the point that is at the intersection of the line of bearing from the anchor nodes to the user.
- At least two TXs needed if absolute angle can be determined by the user
- At least three TXs needed if user determines relative angles



Positioning using relative angle measurements [11],[12]



Positioning using absolute angle measurements [13]

[11] T. S. Rappaport, J. H. Reed, and B. D. Woerner, “Position location using wireless communications on highways of the future,” IEEE Communications Magazine, vol. 34, no. 10, pp. 33–41, Oct. 1996.
[12] C.D. McGillem, T.S. Rappaport. A Beacon Navigation Method for Autonomous Vehicles. *IEEE Transactions on Vehicular Technology*, 38(3):132-139, 1989.
[13] R. P and M. L. Sichitiu, "Angle of Arrival Localization for Wireless Sensor Networks," *2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks*, Reston, VA, 2006, pp. 374-382.

RSS-based Localization

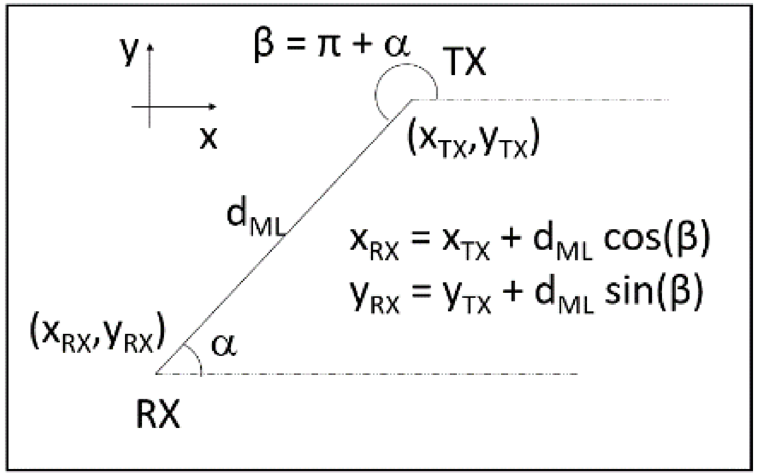
$$PL(d)[dB] = PL_{FS}(d_0)[dB] + 10 \cdot \bar{n} \cdot \log_{10}(\frac{d}{d_0}) + \chi$$

$$PL_{FS}(d_0)[dB] = 20 \cdot \log_{10}(\frac{4\pi d_0}{\lambda})$$

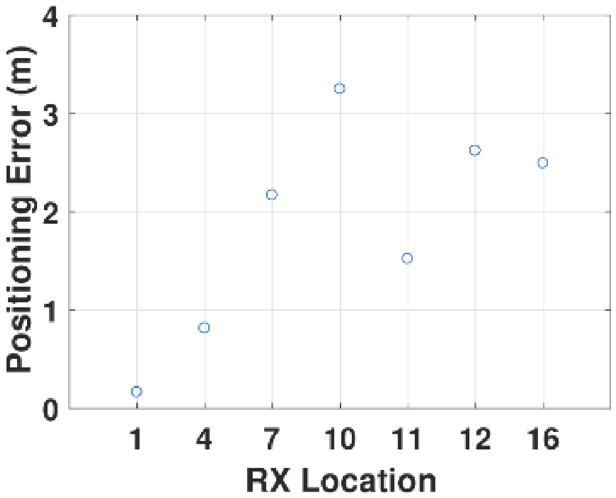
$$d_{ML}[m] = d_0[m] \cdot 10^{(PL[dB]-PL_{FS}(d_0)[dB])/10\cdot\bar{n}}$$

Inaccurate for long distance estimates due to the “flat tail” of the power distance curve

Fusion of AoA and Path Loss



Localization based on the position of a TX in LOS, the TR separation distance and bearing angle between the TX and RX [15].
Manual angular search for the strongest signal at RX – angular resolution of 1°



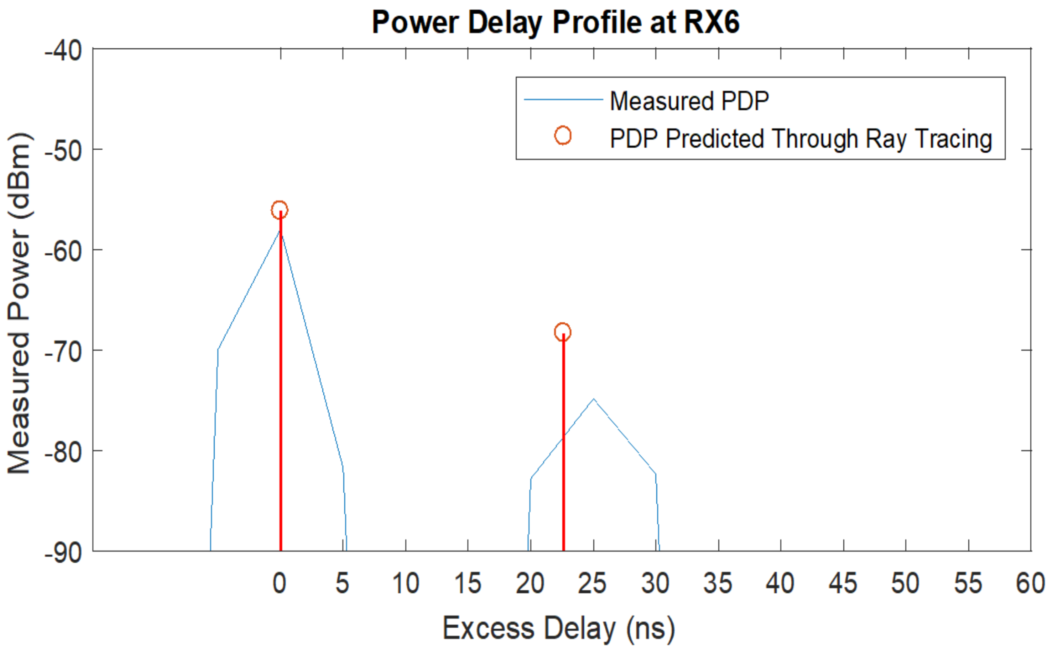
Positioning error based on real-world measurements conducted in [14] at 28 and 73 GHz

Mean error :- 1.86 m
Min error :- 0.16 m
Max error :- 3.25 m

[14] S. Deng, M. K. Samimi, and T. S. Rappaport, “28 GHz and 73 GHz millimeter-wave indoor propagation measurements and path loss models,” in IEEE International Conference on Communications Workshops (ICCW), June 2015, pp. 1244–1250.
[15] O. Kanhere and T. S. Rappaport, “Position Locationing for Millimeter Wave Systems,” GLOBECOM 2018 - 2018 IEEE Global Communications Conference, Abu Dhabi, U.A.E., Dec. 2018, pp. 1–6.

Ray Tracing

- Real-world mmWave measurements - time intensive and expensive
- 2-D ray tracer developed in C++ [15]
- 100 rays launched uniformly in the horizontal plane from TX locations previously measured in [14]
- New source rays generated at each boundary in reflection and transmission directions [16]
- Reflected and transmitted powers and direction calculated using Fresnel's equations [16]



Comparison of the measured and predicted PDP

[14] S. Deng, M. K. Samimi, and T. S. Rappaport, "28 GHz and 73 GHz millimeter-wave indoor propagation measurements and path loss models," in IEEE International Conference on Communications Workshops (ICCW), June 2015, pp. 1244–1250.
[15] O. Kanhere and T. S. Rappaport, "Position Locationing for Millimeter Wave Systems," GLOBECOM 2018 - 2018 IEEE Global Communications Conference, Abu Dhabi, U.A.E., Dec. 2018, pp. 1–6.
[16] S. Y. Seidel and T. S. Rappaport, "Site-specific propagation prediction for wireless in-building personal communication system design," IEEE Trans. Veh. Technol., vol. 43, no. 4, pp. 879–891, Nov. 1994.

Spatial Consistency (1/2)

- *Problems of Existing Drop-based Channel Models*
  - All parameters in one channel realization are generated for a single placement of a particular user [1].
  - There is no successive sample functions for track motion in a local area [2].
  - Beamforming, beam tracking, CSI update need accurate dynamic channel models that can capture the movement of the user and produce continuous channel impulse responses.

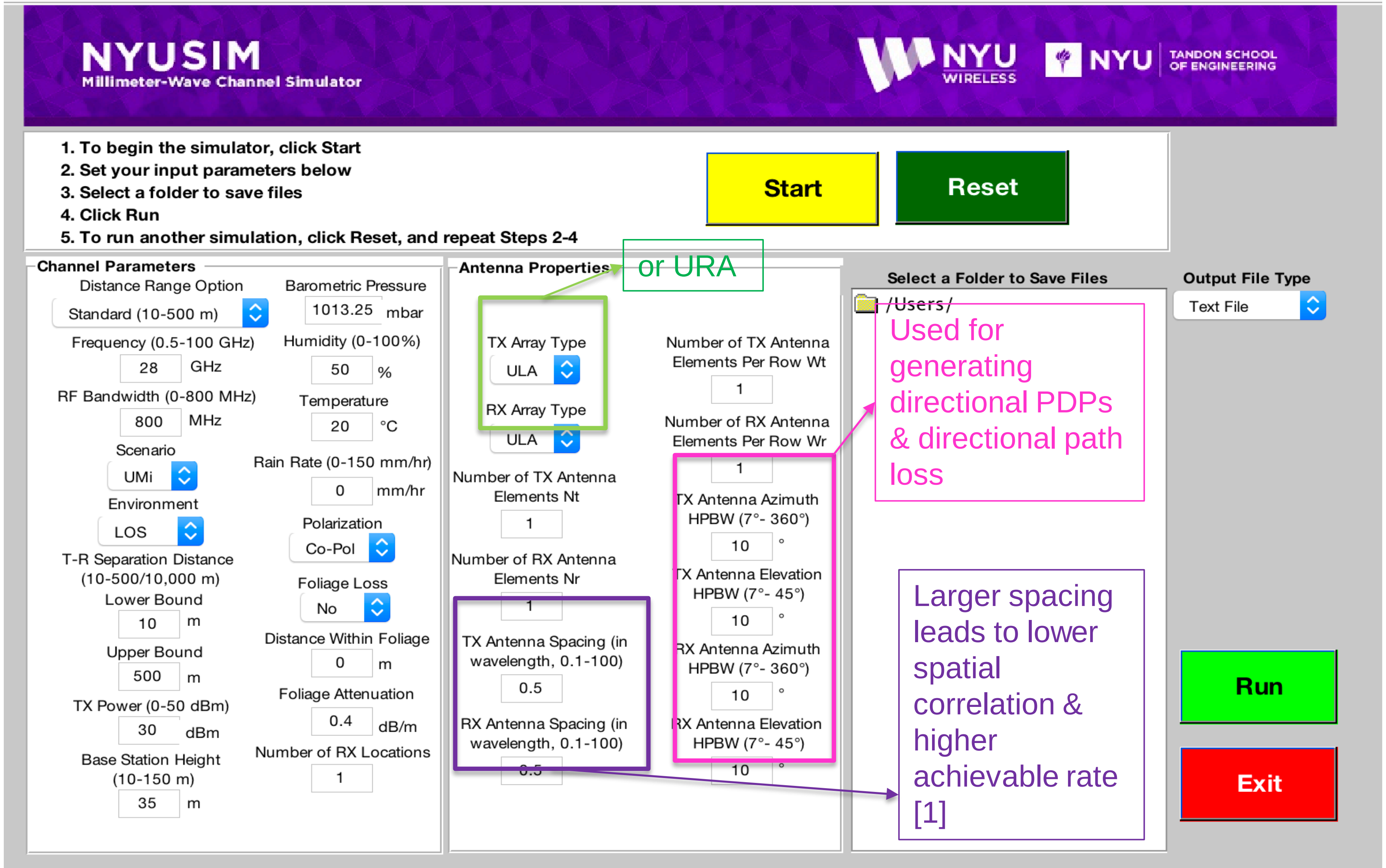
[1] S. Ju and T. S. Rappaport, "Simulating Motion - Incorporating Spatial Consistency into the NYUSIM Channel Model," 2018 IEEE 88th Vehicular Technology Conference Workshops (VTC2018-Fall WKSHPS), Chicago, USA, Aug. 2018, pp. 1-6.
[2] S. Ju, and T. S. Rappaport, "Millimeter-wave Extended NYUSIM Channel Model for Spatial Consistency," 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, UAE, Dec. 2018, pp. 1-6.

Spatial Consistency (2/2)

- *User Cases:*
  - A user terminal (UT) moves in a local area [1]
  - Multiple users are closely spaced
- *Features [2]:*
  - Spatially correlated large-scale parameters such as shadow fading, delay spread, angular spread
  - Time-variant and continuous small-scale parameters such as excess delay, AOA, AOD and power for each multipath component
- *Size of Local Area in Spatial Consistency:*
  - Depends on the correlation distances of large-scale parameters
  - 10 – 15 m in Urban Microcell (UMi) Scenario

[1] 3GPP, "Technical specification group radio access network; study on channel model for frequencies from 0.5 to 100 GHz (Release 14)," 3rd Generation Partnership Project (3GPP), TR 38.901 V14.2.0, Sept. 2017.
[2] M. Shafi et al., "Microwave vs. millimeterwave propagation channels: Key differences and impact on 5G cellular systems," to appear in IEEE Communications Magazine, Nov. 2018.

NYUSIM Channel Simulator



30 Input parameters [2]

Open-source with more than 50,000 downloads [3]

Drop-based Monte Carlo simulation to generate a channel impulse response (CIR) at each drop (i.e., user location)

Physical-level simulations of the downlink channel between a base station and a UT

[1] J. Lota, S. Sun, T. S. Rappaport, and A. Demosthenous, “5G uniform linear arrays with beamforming and spatial multiplexing at 28, 37, 64, and 71 GHz for outdoor urban communication: A two-level approach,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 9972-9985, Nov. 2017.
[2] 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), May 2017.
[3] NYUSIM, http://wireless.engineering.nyu.edu/nyusim/

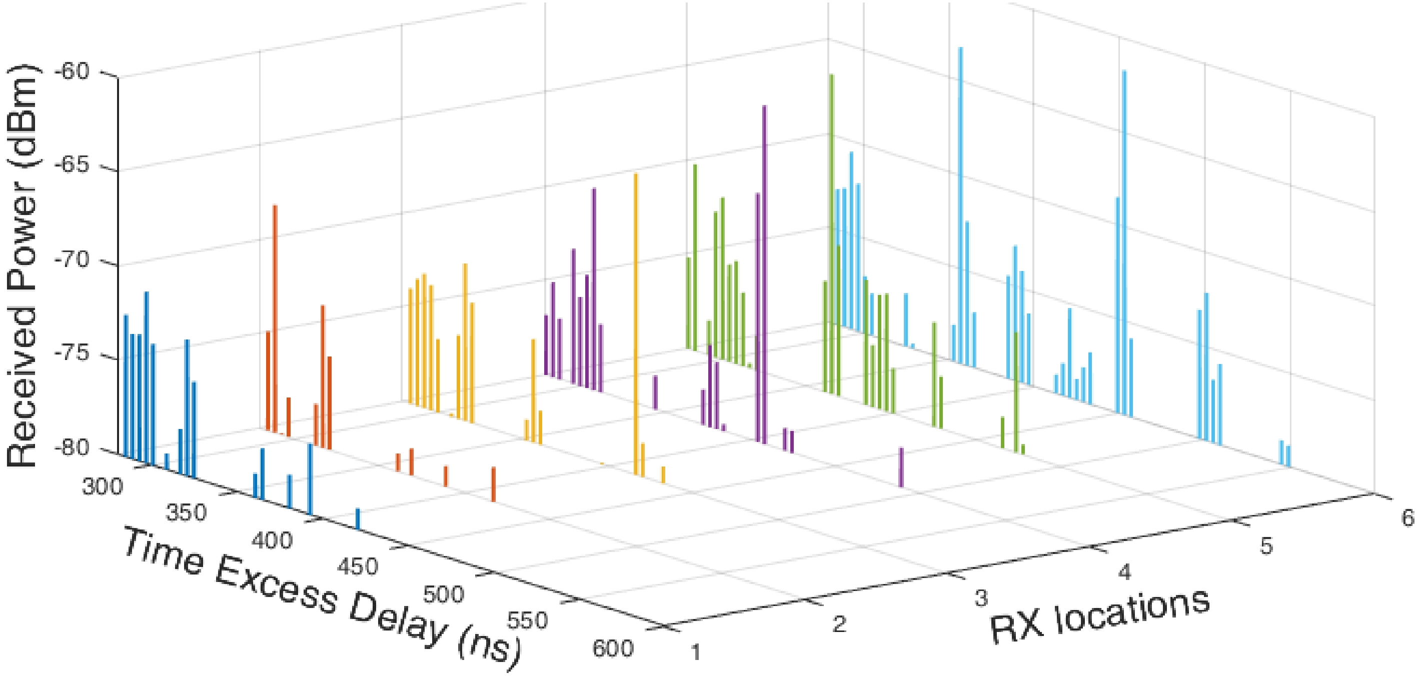
Local Area Measurements for Spatial Consistency (1/2)

- ❑ Omnidirectional PDPs at 16 RX locations in a UMi street canyon in downtown Brooklyn at 73 GHz.
- ❑ The distance between two successive RX locations was 5 m.
- ❑ The receiver moved from RX81(‘1’ at the ‘RX locations’ axis) to RX96 (‘16’ at the ‘RX locations’ axis).
- ❑ The T-R separation distance varied from 81.5 m to 29.6 m.
- ❑ The visibility condition changed at RX 91 and RX 92 from NLOS to LOS.

Measurement locations and LOS/NLOS conditions [1]

[1] T. S. Rappaport, G. R. MacCartney, Jr., S. Sun, H. Yan, and S. Deng, “Small-scale, local area, and transitional millimeter wave propagation for 5G communications,” IEEE Transactions on Antennas and Propagation, Dec. 2017

Local Area Measurements for Spatial Consistency (2/2)



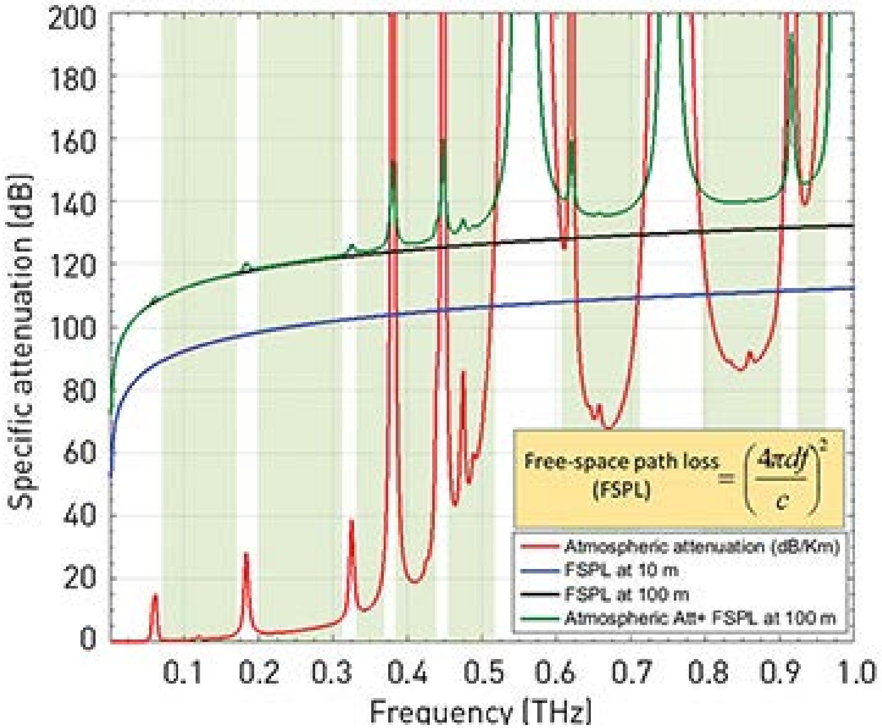
# of time clusters	RX locations
3	81, 82
4	83, 84
6	85, 86

Conclusion:
The correlation distance of the number of time clusters is about 10 m in a UMi street canyon scenario [1].

Omnidirectional PDPs at RX81-RX86 to study the correlation distance of large-scale parameters. The distance between two successive RX locations was 5 m. The PDPs at RX81 and RX82 are similar; the PDPs at RX83 and RX84 are similar; the PDPs at RX85 and RX86 are similar.

[1] S. Ju, and T. S. Rappaport, “Millimeter-wave Extended NYUSIM Channel Model for Spatial Consistency,” 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, UAE, Dec. 2018, pp. 1-6.

Sub-THz and THz Frequencies



- ❑Massive bandwidth
- ❑Largely unexplored
- ❑> 100 m range possible in LOS links assuming
  - Active antenna arrays
  - Modest power (~ 20 dBm before antenna gain)
- ❑Focus bands in this work:
  - 140, 220, 340, 680, 1080 GHz

Haymen Shams and Alwyn Seeds, Photonics, Fiber and THz Wireless Communication, Optics and Photonics News 2017

Use Cases for THz

- ❑Cellular backhaul
- ❑Immersive video
- ❑Edge computing, cognition
- ❑Aerial communications
- ❑Wireless chip-to-chip
- ❑Wireless LAN
- ❑6G

- ❑Something you can still invent!

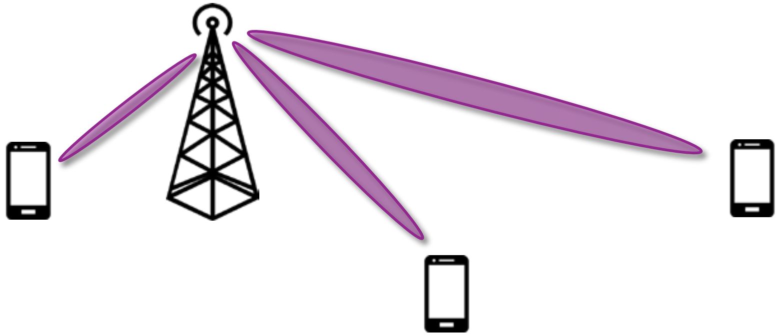
DJI Matrice 600 Pro
(payload 6 Kg)

Challenges and Solutions

Challenge	Solutions
ADC and baseband processing power consumption RF sources/power efficiency	• Low resolution signal processing • Hybrid beamforming • Low-complexity MIMO algorithms • Low-complexity imaging • GaAs, GaN
Adaptive beamforming and directional sensing	• Compressed sensing tracking • Fully digital architectures • Fast protocols for directional search / access • Coordinated distributed sensing
End-to-end effects of channel intermittency	• Multi-connectivity, fast handover • Fast congestion control

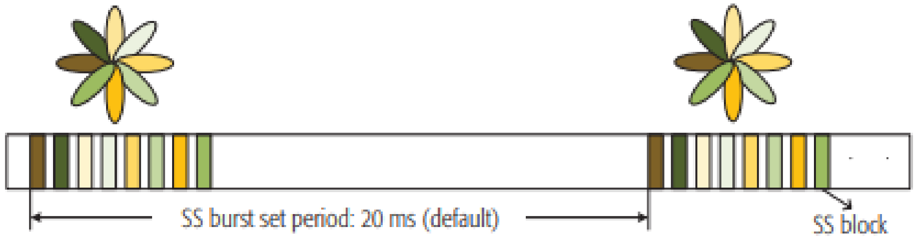
Low Resolution Fully Digital THz Transceivers

- Fully digital:
  - Can search in all directions simultaneously
  - Valuable in mobile environments
  - Multiple access / spatial multiplexing
- Low-resolution ADCs:
  - Key limitation of fully digital is power consumption
  - Power scales as $P = cf2^b$, b = number of bits
  - Reduces power with low number of bits (b=2−4)
- Challenges
  - Potential in band distortion
  - Out-of-band emissions
  - Digital signaling between chips may be higher power



Fast Search with Fully Digital

- Fully digital enables much faster search
- Cellular example: UE can scan all directions in a single SS burst period
  - Can dramatically reduce idle mode transition time
- Other use cases for THz:
  - Aerial communications, low-latency recovery from blockage



Assumptions: 3GPP Umi model extrapolated to 140 GHz + 20 dB additional path loss, d=100 m, 3GPP NR numerology with 240 kHz SCS

UE RX	gNB PSS TX	PSS length (us)	PSS overhead	Sync delay (ms)
Digital	Directional	4.46	0.065	26.14
Analog	Directional	4.46	0.065	320.8

Power Consumption Estimates (mmWave)

Receiver: 16 RX, 1 GHz sampling

MIMO architecture	LNA (mW)	Phase shifter	Combiner	Mixer	ADC	Total
Analog	160	317	19.5	14.2	33.3	544
Hybrid (K=2)	160	634	39	28.4	66.6	928
Fully digital (8 bits)	160			227	532	920
Fully digital (4 bits)	160			227	33.3	421

- Low resolution ADC can significantly reduce power
- Fully digital is preferable at high number of streams

Transmitter: 16 TX, 1 GHz sampling

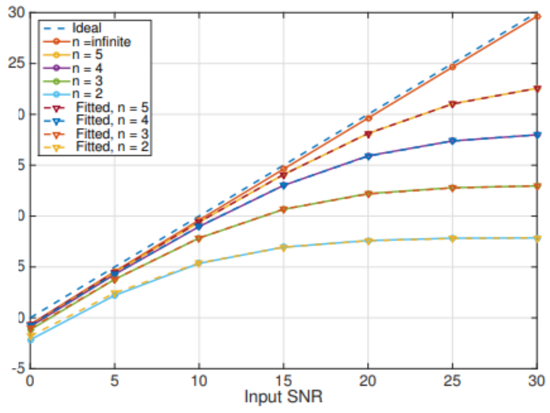
High power: 23 dBm, Medium power: 13 dBm total (before antenna gain)

MIMO architecture	PA (High / Med)	PS	Splitter	Mixer	DAC	Total (High / Med)
Analog	800 / 80	317	19.5	14.2	34.6	1185 / 465
Hybrid (K=2)	800 / 80	634	39	28.4	69.2	1570 / 850
Fully digital (8 bits)	800 / 80			227	554	1581 / 861
Fully digital (4 bits)	800 / 80			227	34.6	1062 / 342

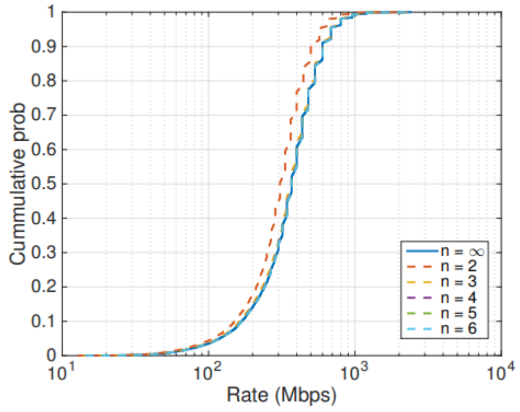
- PA power is dominant at high TX power
    - TX power control, PA efficiency are key
- At moderate TX power, low-res fully digital is preferable

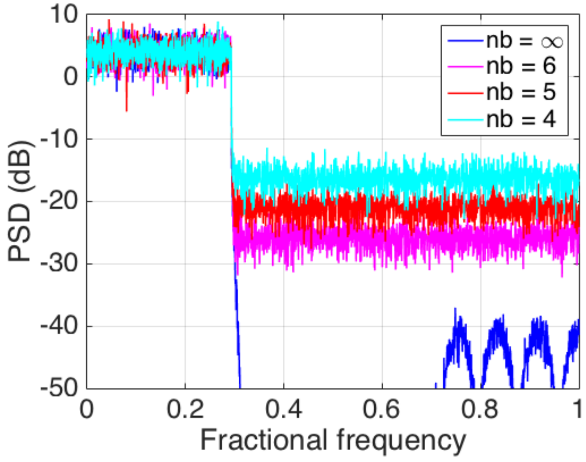
Low-Resolution Fully Digital Performance

Effective SNR



Input SNR





Link-level simulation

- Low-res limits peak SNR
- Minimal effect at low SNR

Cellular simulation

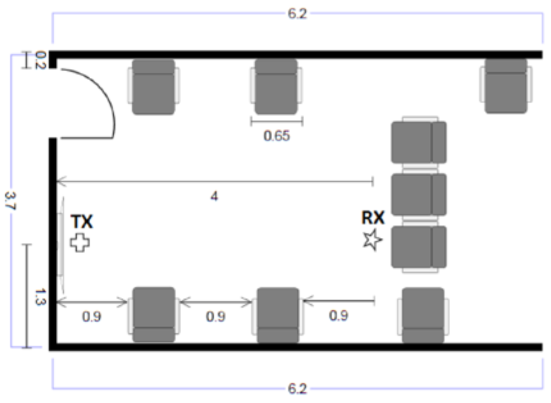
- 2-4 bits is sufficient
- Most users in low SNR
- Esp. with beamforming

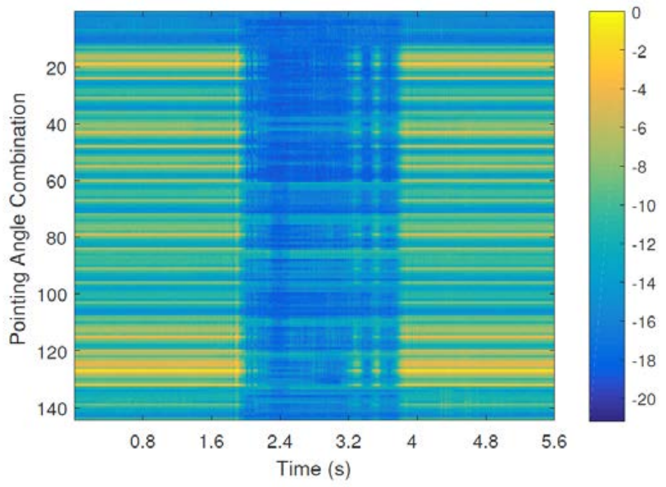
Out of band emissions

- Still a challenge
- Need better filtering
- Delta-Sigma or analog

S. Dutta, C. N. Barati, A. Dhananjay and S. Rangan, "5G millimeter wave cellular system capacity with fully digital beamforming," *IEEE Asilomar, 2017*

Understanding Blockage Dynamics





- MmWave and THz signals are blocked by many materials
- Key issue for mobile system design
- 60 GHz Phased array channel sounding system
  - Measures blockage in multiple directions simultaneously
- Project is to reproduce results in THz frequencies
  - Getting phased arrays from SRC collaboration

Slezak et al, Understanding End-to-End Effects of Channel Dynamics in Millimeter Wave 5G New Radio, to appear IEEE SPAWC 2018

NATIONAL INSTRUMENTS

SONY

MmWave and THz ns3 Module

- First, open-source mmWave module
  - End-to-end
  - Detailed channel models (statistical, ray tracing, 3GPP, …)
  - Already demonstrated in many new studies
- Used by several groups
  - Ericsson, Nokia, European projects, …
- Seeking to build THz module
  - Focus initially on channel models
  - Key use cases: robotics, aerial communication

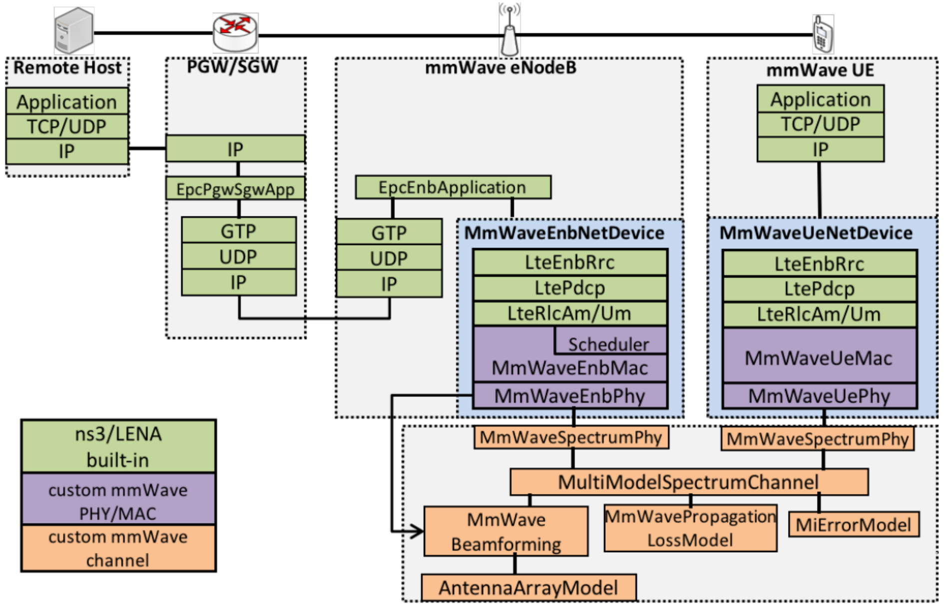


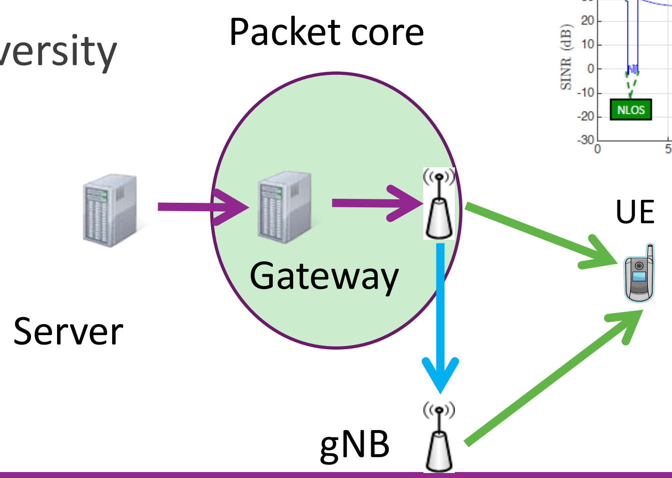
Figure 1: Class diagram of the end-to-end mmWave module.

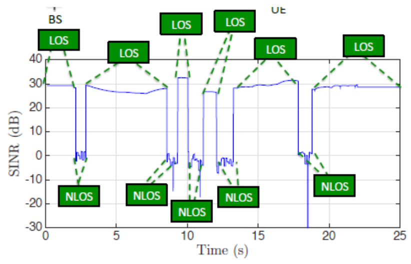
Mezzavilla et al, "End-to-End Simulation of 5G mmWave Networks", 2017

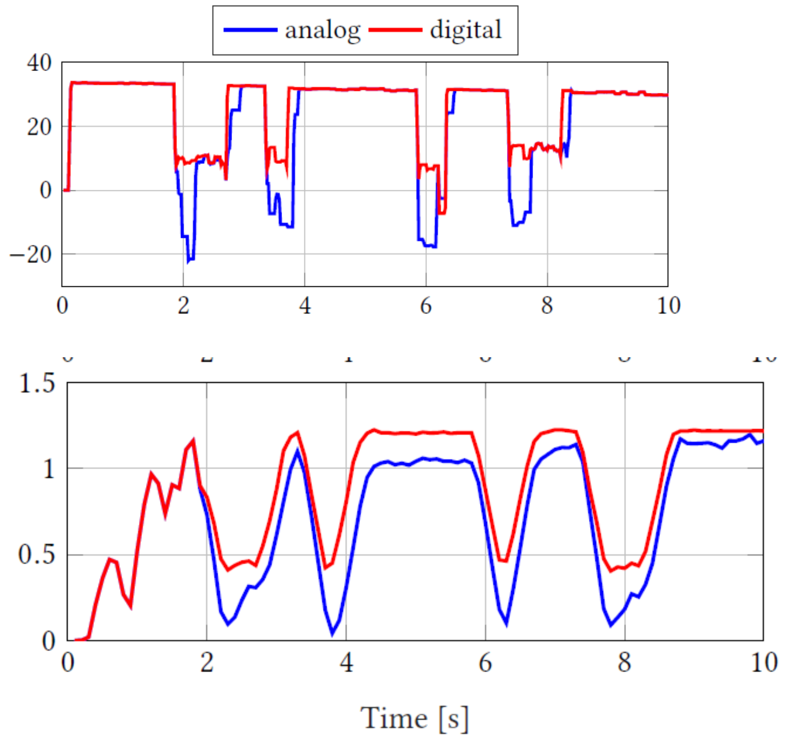
Download at ns-3 app store: https://apps.nsnam.org/

End-to-end Performance

- MmWave and THz Link-layer:
  - High peak rate, but intermittent
- Adaptation dependent on many factors:
  - TCP protocol
  - Server placement (edge / remote)
  - Buffer management
  - Beam search
  - Macro-diversity
  -





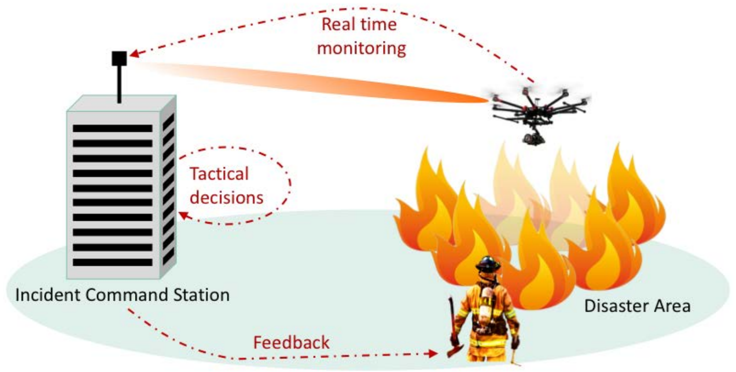


Herranz et al, A 3GPP NR Compliant Beam Management Framework to Simulate End-to-End mmWave Networks, ACM MSWIM 2018 (to appear)

Projects

- ComSenTer
  - UCSB lead (PI: Mark Rodwell)
  - 21 faculty, ~$21 million total
  - Thrust leaders: Mitra (devices), Ali Niknejad (circuits), Rangan (systems)
  - THz devices, circuits and systems
  - Focus on communications and sensing

- NIST Public Safety Communications
  - PI Rangan, PM Marco Mezzavilla
  - Focus on aerial communications



M. Mezzavilla *et al.*, "Public Safety Communications above 6 GHz: Challenges and Opportunities," in *IEEE Access*, vol. 6, pp. 316-329, 2018.

Thank You