# Wireless Communication and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond

Theodore S. Rappaport, Yunchou Xing, Shihao Ju, Ojas Kanhere

Millimeter Wave Coalition

February 28, 2019

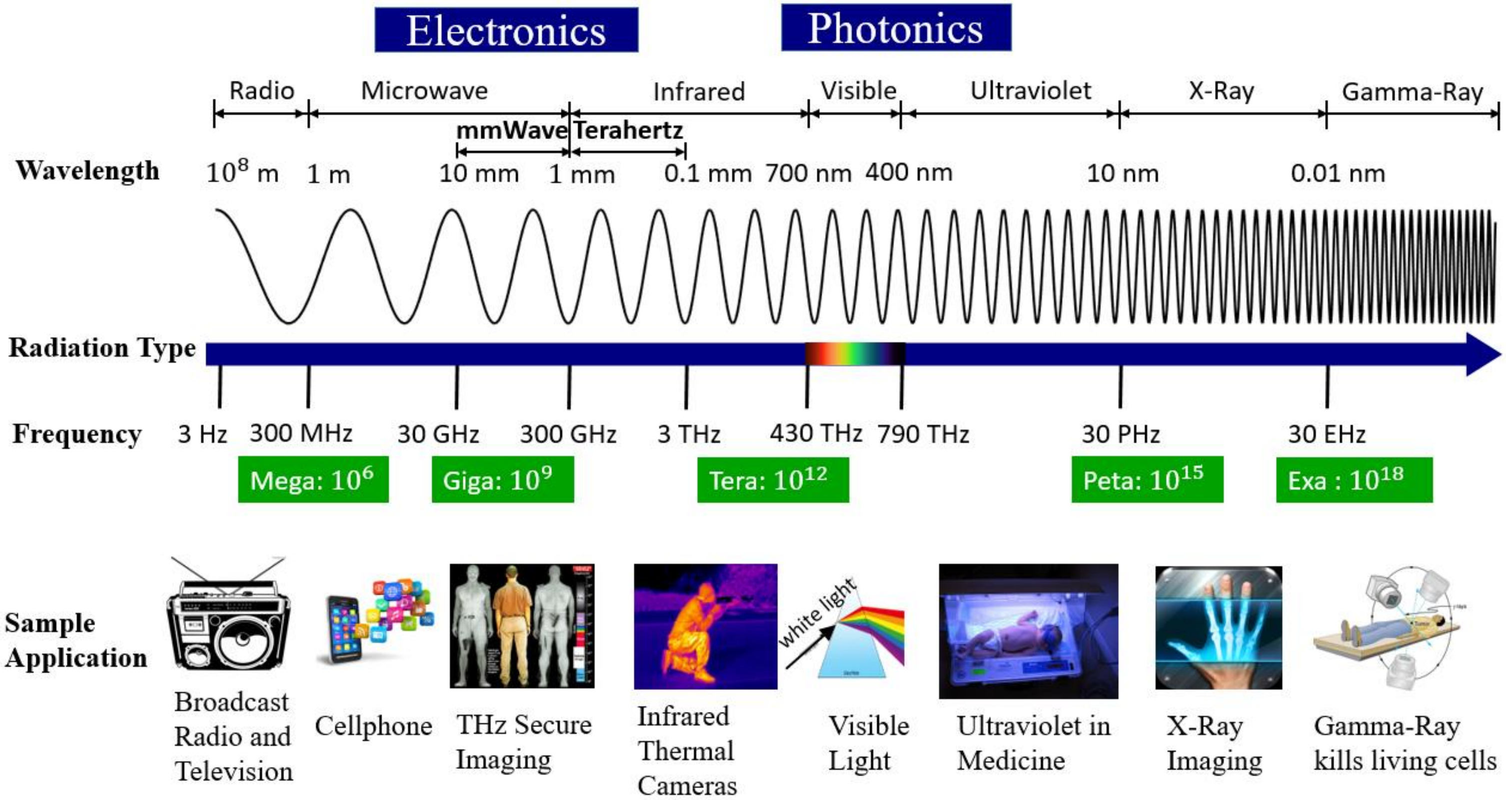
This work is supported by the NYU WIRELESS Industrial Affiliate Program and National Science Foundation (NSF) (Award Number: 1702967, 1731290 1555332, 1302336, and 1320472).

# Industrial Affiliates

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

This work is supported by the NYU WIRELESS Industrial Affiliate Program and National Science Foundation (NSF) (Award Number: 1702967, 1731290 1555332, 1302336, and 1320472).

# Electromagnetic Spectrum & Applications





[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Alkhateeb, G. C. Trichopoulos, A. Madanayake, S. Mandal, “Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond (Invited),” IEEE ACCESS, submitted Feb. 2019.

# Evolution of Wireless Technologies



1933

FM Radio
(~100 MHz)

1973

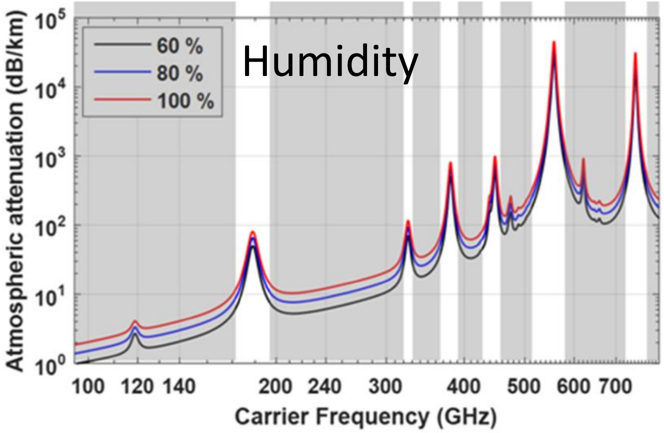
First handheld
phone
(~850 MHz)

2003

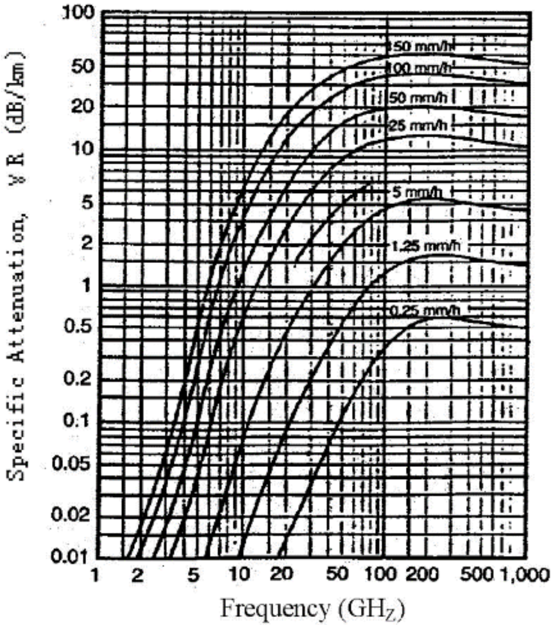
WIFI (~2.4 and
5 GHz)

2019

Foldable Smart
Phone (~3.5 GHz)



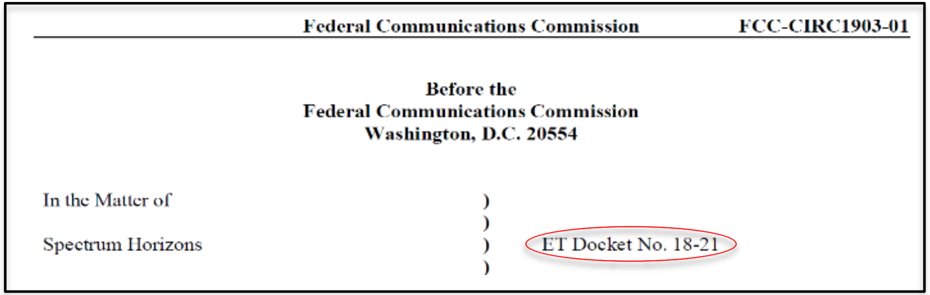

Rain Attenuation




**90 Years Just Sub-6 GHz!**

[2] T. S. Rappaport *et al*. "State of the art in 60-GHz integrated circuits and systems for wireless communications," Proceedings of the IEEE, vol. 99, no. 8, pp. 1390–1436, Aug. 2011.
[3] Q. Zhao and J. Li, ‘‘Rain attenuation in millimeter wave ranges,’’ in Proc. IEEE Int. Symp. Antennas, Propag. EM Theory, Oct. 2006, pp. 1–4.
[4] mmWave Coalition's NTIA Comments, Filed Jan. 2019. http://mmwavecoalition.org/mmwave-coalition-millimeter-waves/mmwave-coalitions-ntia-comments/
[29] J. Ma et. al., "Channel performance for indoor and outdoor terahertz wireless links," APL Photonics, vol. 3, no. 5, pp. 1–13, Feb. 2018.

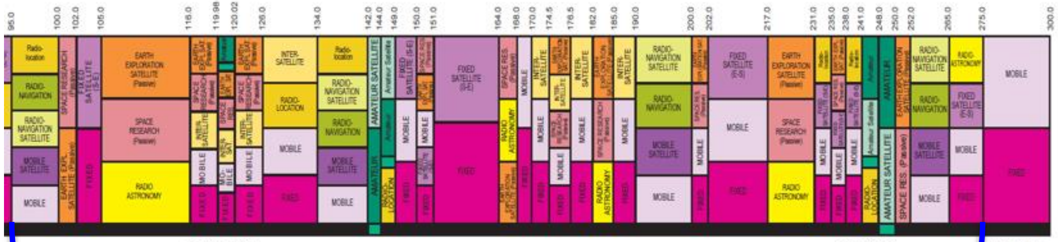
# FCC Proposes “Spectrum Horizons” > 95 GHz


Federal Communications Commission FCC-CIRC1903-01

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

In the Matter of )
)
Spectrum Horizons ) ET Docket No. 18-21
)

Report and Order ET Docket 18-21 published on Feb 22nd, 2019




- Experimental licenses for 95 GHz to 3 THz - **Spectrum Horizons.**
- 21.2 GHz **Unlicensed Spectrum** to be allocated.
- Rules on Licensed spectrum deferred until sufficient technical and market data is obtained.

http://mmwavecoalition.org/wp-content/uploads/2019/02/DOC-356297A1-FCC-Report-Order.pdf

# FCC First Report and Order—ET Docket 18-21

Caution required – sharing spectrum!

**Spectrum Horizons Experimental Radio Licenses**

- Frequency within **95 GHz to 3 THz**
- No interference protection from pre-allocated services.
- Interference analysis before license grant.

FCC will Vote on March 15th 2019!
"Behold the Ides of March"

**Unlicensed Operation**

- Maximum EIRP of 40 dBm (average) and 43 dBm (peak) for **mobile**.
- Maximum EIRP of $82-2*(51-G_{TX})$ dBm (average) and $85-2*(51-G_{TX})$ dBm (peak) for **fixed point-to-point**.
- Out-of-band emission limit 90 pW/cm$^2$ at three meters.

| Frequency Band (GHz) | Contiguous Bandwidth (GHz) |
|---|---|
| 116-123 | 7 |
| 174.8-182 | 7.2 |
| 185-190 | 5 |
| 244-246 | 2 |
| Total | 21.2 |

http://mmwavecoalition.org/wp-content/uploads/2019/02/DOC-356297A1-FCC-Report-Order.pdf

# mmWave Coalition

- Frequencies above 95 GHz are seriously under-developed in the U.S. because of a 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 [4].

- 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.

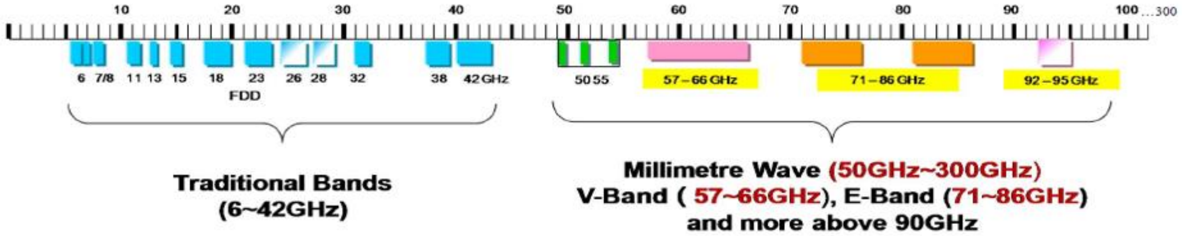
- Annual Contribution is $5k for a large company, $100 for an Academic Institution, and $1.5k for others. Each member can nominate one person to act as its “Principal” representing it on the Steering Committee (currently chaired by Nokia).

[4] mmWave Coalition’s NTIA Comments, Filed Jan. 2019. http://mmwavecoalition.org/mmwave-coalition-millimeter-waves/mmwave-coalitions-ntia-comments/

# Other Activities on Spectrum Above 95 GHz



- **Europe**: ETSI ISG mWT: studying applications/use cases of millimeter wave spectrum (50 GHz - 300 GHz).


- **ITU-R**: WRC-19 Agenda Item 1.15 will identify applications 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

# mmWave & THz Applications

| mmWave & THz Applications—the potential for 6G [1] | |
|---|---|
| Wireless Cognition | Robotic Control [27, 28]<br>Drone Fleet Control [27] |
| Sensing | Air quality detection [5]<br>Personal health monitoring system [6]<br>Gesture detection and touchless smartphones [7]<br>Explosive detection and gas sensing [8] |
| Imaging | See in the dark (mmWave Camera) [9]<br>High-definition video resolution radar [10]<br>Terahertz security body scan [11] |
| Communication | Wireless fiber for backhaul [12]<br>Intra-device radio communication [13]<br>Connectivity in data centers [14]<br>Information shower (100 Gbps) [15] |
| Positioning | Centimeter-level Positioning [9,16] |

[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Alkhateeb, G. C. Trichopoulos, A. Madanayake, S. Mandal, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond (Invited)," IEEE ACCESS, submitted Feb. 2019.

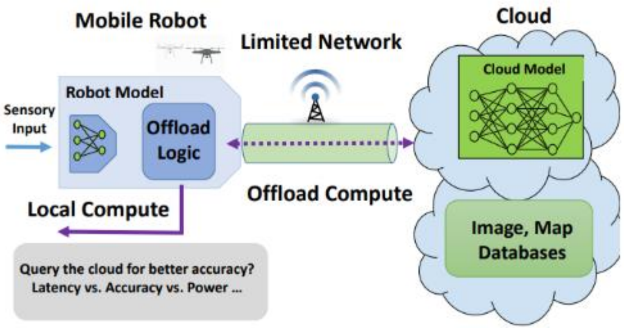
# Wireless Cognition

Autonomous cars

Drones Deliver

Robotics

Holographic Imaging and Spatial cognition

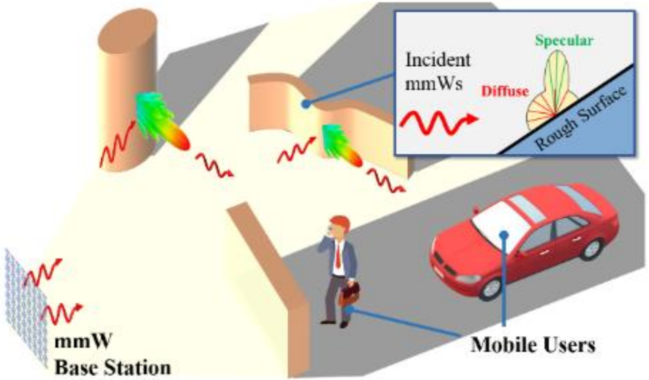



Wireless Cognition （Network Offloading） [17]

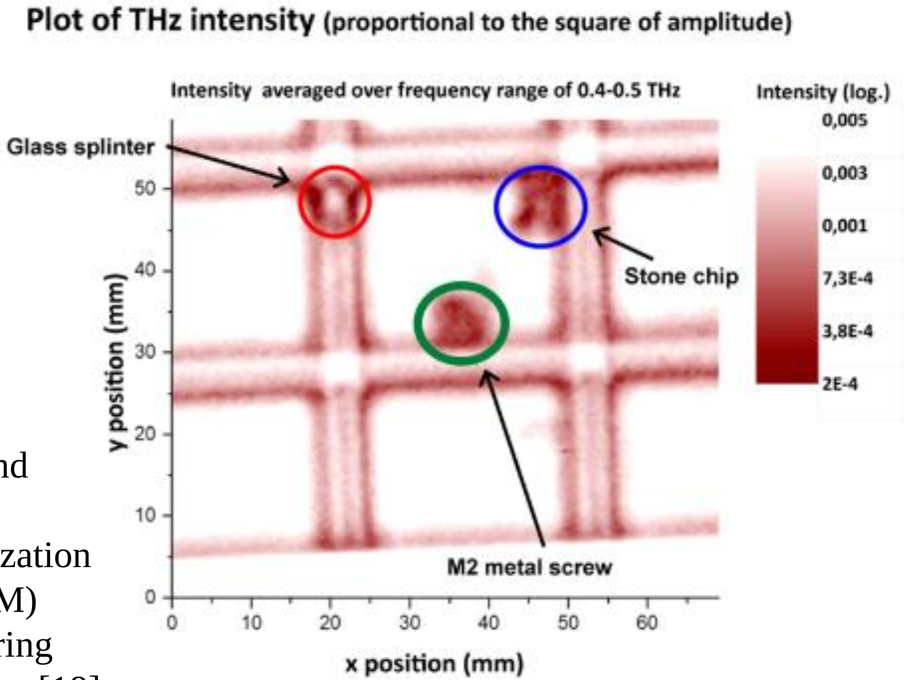
https://www.independent.co.uk/life-style/gadgets-and-tech/driverless-cars-travel-technology-government-control-autonomous-cars-a8413301.html
https://smallbiztrends.com/2016/03/delivery-drones-grounded-by-faa.html
https://www.arabianbusiness.com/technology/397057-ai-to-add-182bn-to-uae-economy-by-2035

[17] Chinchali S. et. al., Network Offloading Policies for Cloud Robotics: a Learning-based Approach. arXiv preprint arXiv:1902.05703. 2019 Feb 15.

Body scanner using THz imaging to detect explosives [1]




mmWave imaging and communications for Simultaneous Localization And Mapping (SLAM) exploiting the scattering properties at mmWave [18]

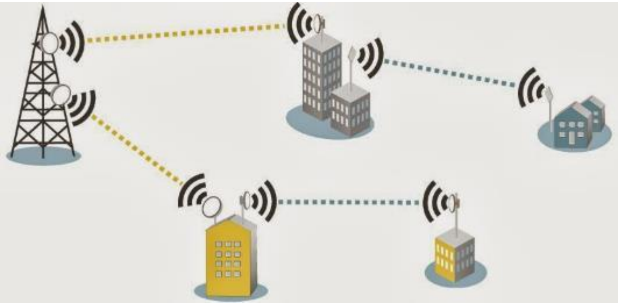



Glass, rock and a metal screw identified in a chocolate bar using THz imaging [17]

[1] http://terasense.com/products/body-scanner/
[17] C. Jördens, F. Rutz, M. Koch: Quality Assurance of Chocolate Products with Terahertz Imaging; European Conference on Non-Destructive Testing, 2006 – Poster 67
[18] M. Aladsani, A. Alkhateeb, and G. C. Trichopoulos, "Leveraging mmWave Imaging and Communications for Simultaneous Localization and Mapping," International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Brighton, UK, May 2019.

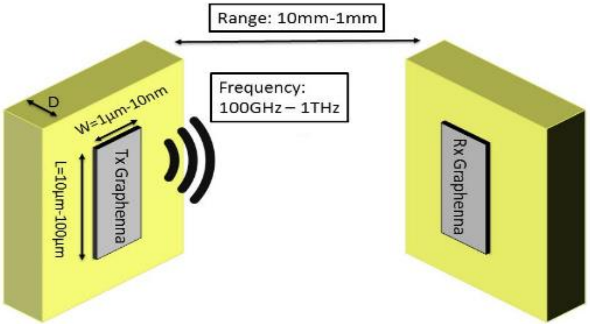
# Wireless Communications





100 Gbps ~ 1 Tbps backhaul links over rooftops [12]

Short-range THz wireless connectivity in data centers [2]




On-chip & chip to chip Terahertz communication links [20]

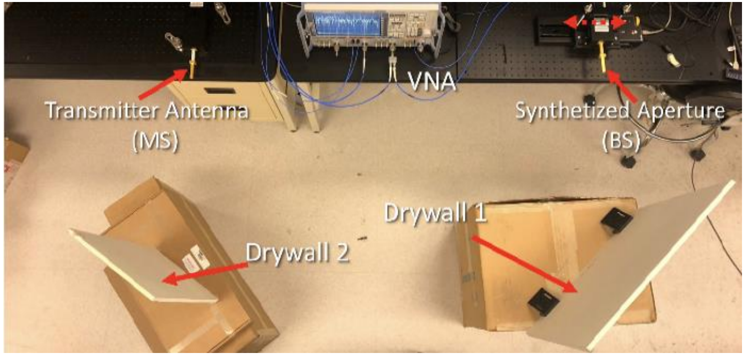
[2] http://terapod-project.eu/wp-content/uploads/2018/03/Re-imagining-data-centres-with-THz.pdf
[12] T. S. Rappaport, et al., “Overview of millimeter wave communications for fifth-generation (5G) wireless networks-with a focus on propagation models,” IEEE Trans. on Ant. and Prop., vol. 65, no. 12, pp. 6213–6230, Dec. 2017.
[20] S. Abadal, A. Marruedo, et al., "Opportunistic Beamforming in Wireless Network-on-Chip", in Proceedings of the ISCAS ’19, Sapporo, Japan, May 2019.

# Precise Positioning (1/2)

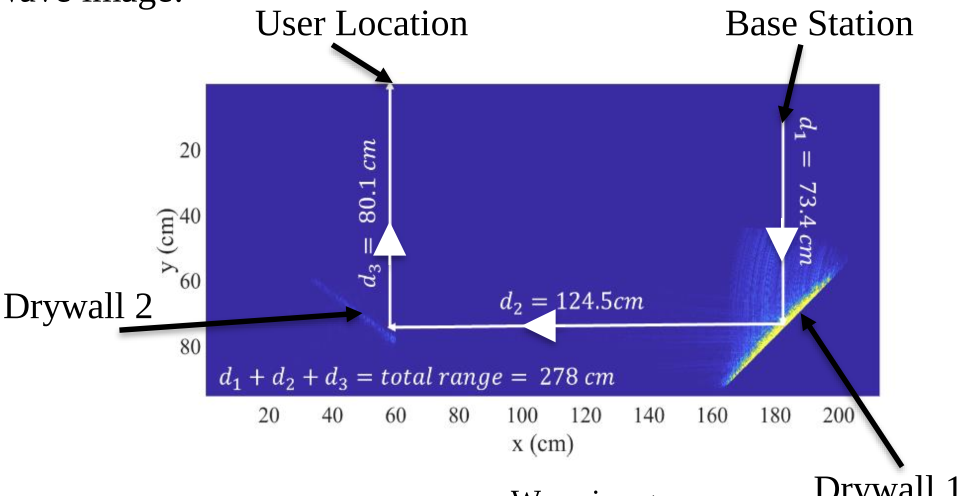


cm-level localization at mmWave and THz, assuming materials are perfect reflectors [1,18]

1. mmWave image of surrounding environment constructed
2. User location is projected on the constructed mmWave image.




Experimental Setup




mmWave image

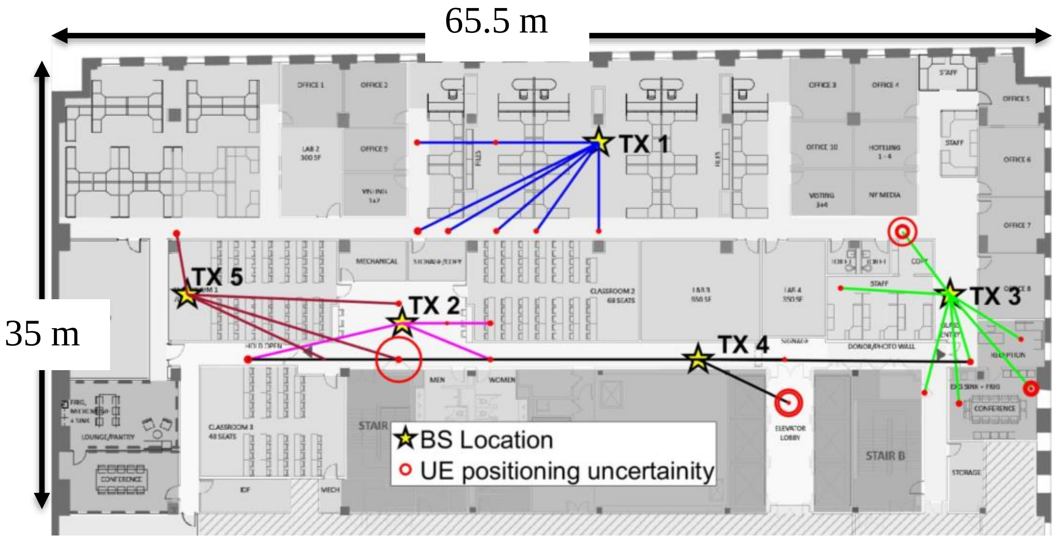

[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Alkhateeb, G. C. Trichopoulos, A. Madanayake, S. Mandal, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond (Invited)," IEEE ACCESS, submitted Feb. 2019.

[18] M. Aladsani, A. Alkhateeb, and G. C. Trichopoulos, "Leveraging mmWave Imaging and Communications for Simultaneous Localization and Mapping," in International Conference on Acoustics, Speech, and Signal Processing (ICASSP), May 2019, pp. 1–4.

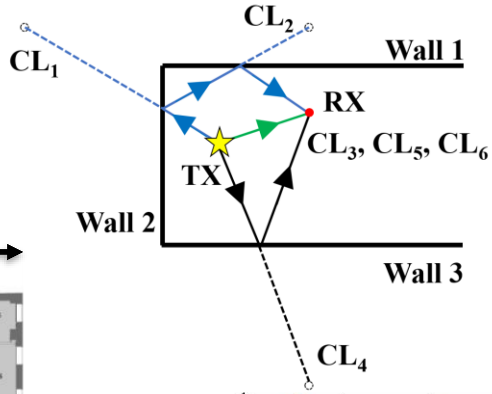
# Precise Positioning (2/2)



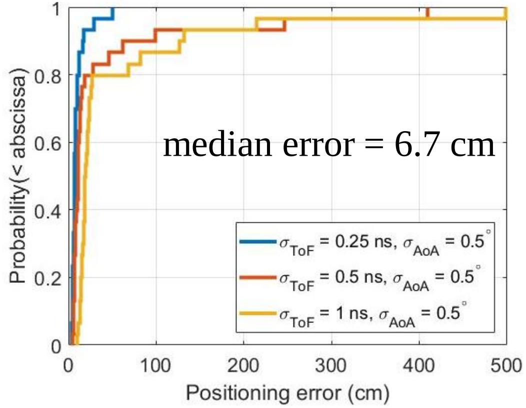
- cm-level localization with map, AoA, and ToF information at mmWave & THz [1].
- Materials ***not*** assumed to be perfect reflector at mmWave




3-D error spheres depicting typical positioning accuracy on map




The map of the environment used to retrace signal paths



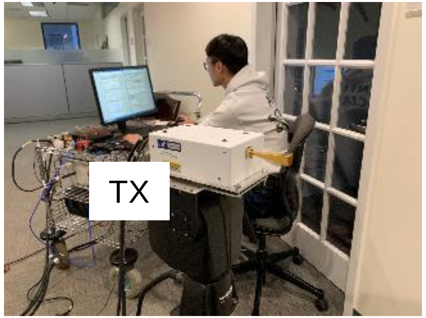


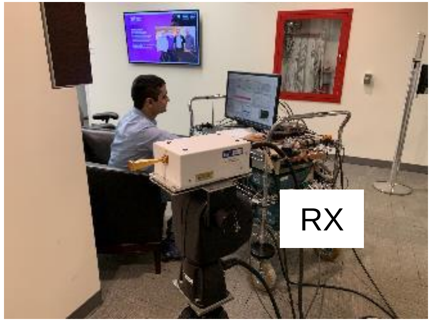
[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Alkhateeb, G. C. Trichopoulos, A. Madanayake, S. Mandal, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond (Invited)," IEEE ACCESS, submitted Feb. 2019.

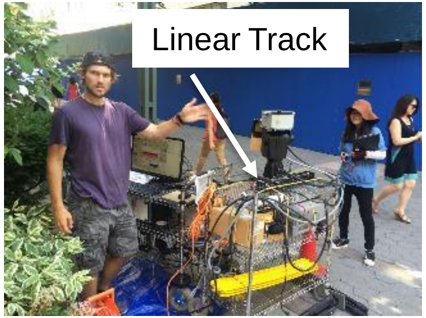
[16] O. Kanhere and T. S. Rappaport, "Position locationing for millimeter wave systems," in IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

# 140 GHz Broadband Channel Sounder at NYU WIRELESS

## Conducting measurements [21]





## 140 GHz broadband channel sounder demo at Brooklyn 5G Summit [22]

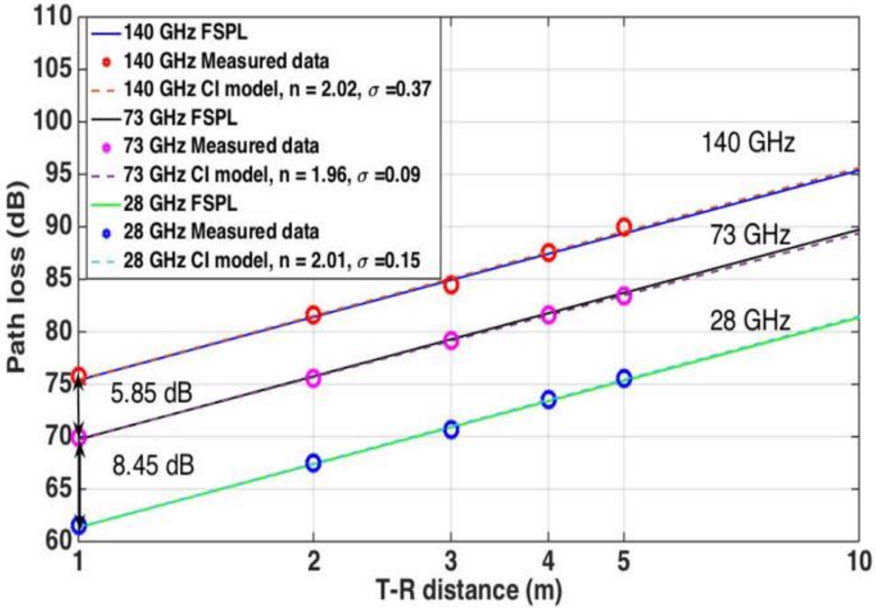

[21] Y. Xing and T. S. Rappaport, “Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz,” IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.
[22] https://ieeetv.ieee.org/event-showcase/brooklyn5g2018

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

## NYU 140 GHz Channel Sounder System

| 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<br>10 dBm (damage limit) |
| Downconverter RF input | -15 dBm typically<br>0 dBm (damage limit) |
| TX output power | 0 dBm |
| Antenna Gain | 25 dBi / 27 dBi |
| Antenna HPBW | 10º / 8º |
| Antenna Polarization | Vertical / Horizontal |

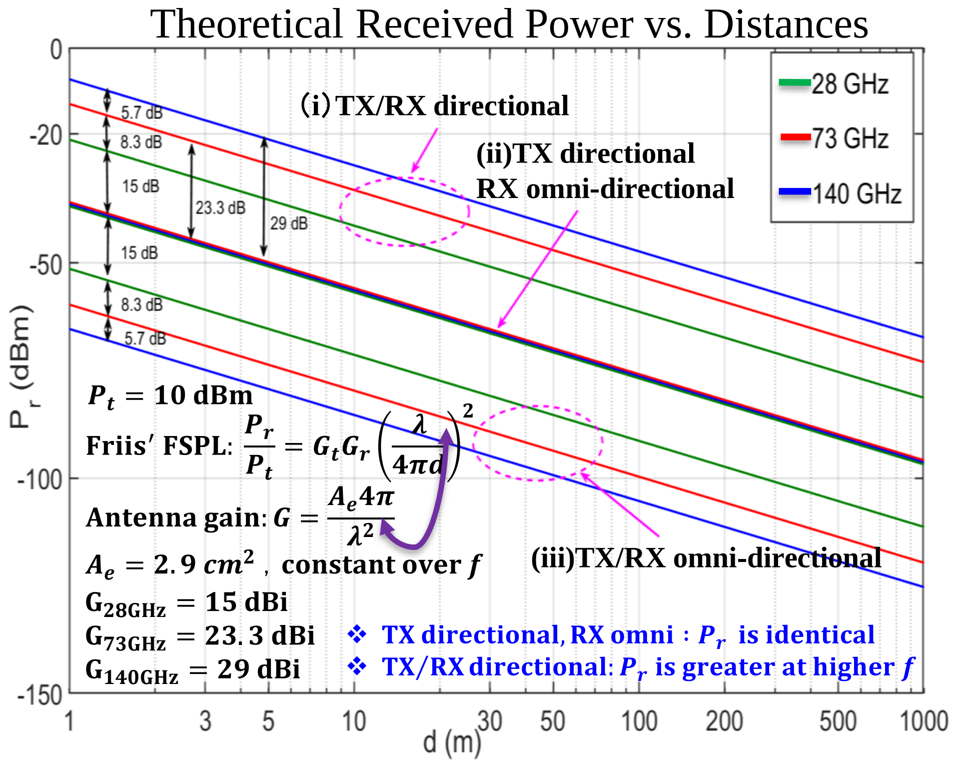
**FSPL verifications following the proposed method**
at 28, 73, and 140 GHz [23] (after removing antenna gains)




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


[23] 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.

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




**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 |

**DIRECTIONAL ANTENNAS WITH EQUAL APERTURE HAVE MUCH LESS PATH LOSS AT HIGHER FERQUENCIES ([24] Ch.3 Page 104) !!!**

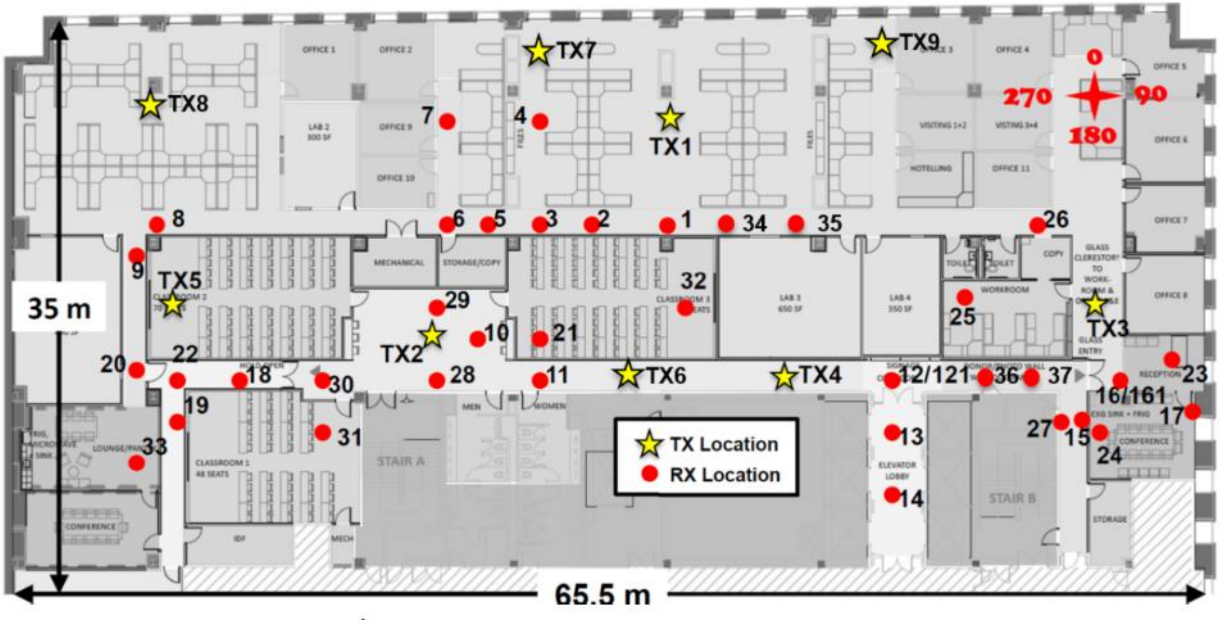
**PENETRATION LOSS INCREASES WITH FREQUENCY BUT THE AMOUNT OF LOSS IS DEPENDENT ON THE MATERIAL [21]**

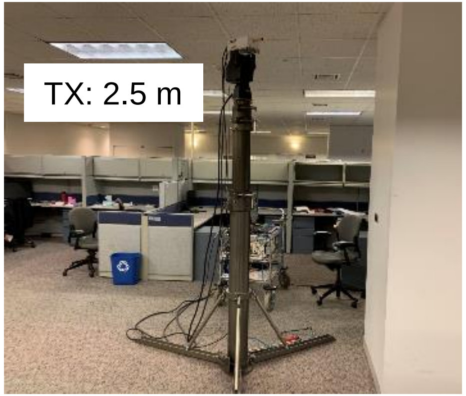

[24] T. S. Rappaport, et. al., "Millimeter Wave Wireless Communications," Pearson/Prentice Hall c. 2015.
[21] Y. Xing and T. S. Rappaport, "Propagation Measurement System and Approach at 140 GHz-Moving to 6G and Above 100 GHz," in IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

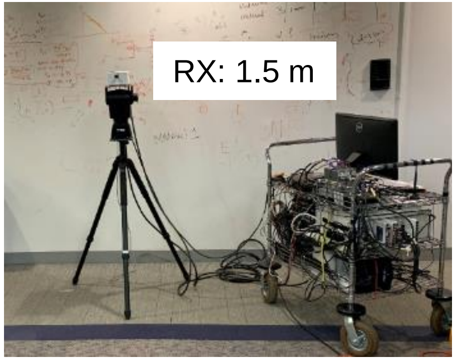
NYU TANDON SCHOOL OF ENGINEERING

# Ongoing 140 GHz Measurement Campaign

NYU WIRELESS



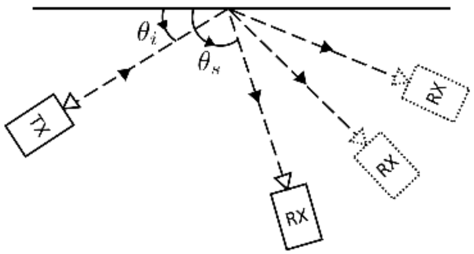




Maps of 2 MetroTech Center 9th floor. There are 9 TX locations (stars) and 37 RX locations (dots). The 140 GHz indoor measurement campaign will use the same measurement locations as used at 28 and 73 GHz, providing 48 TX-RX combinations ranging from 4 to 48 m [25, 21].

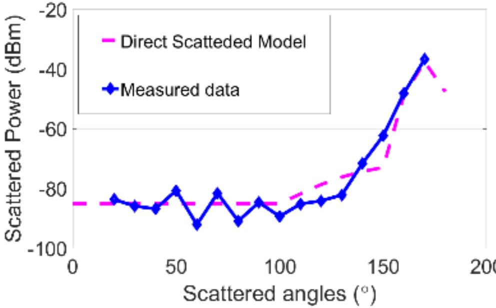

[25] G. R. Maccartney, T. S. Rappaport, S. Sun and S. Deng, "Indoor Office Wideband Millimeter-Wave Propagation Measurements and Channel Models at 28 and 73 GHz for Ultra-Dense 5G Wireless Networks," in *IEEE Access*, vol. 3, pp. 2388-2424, 2015.

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

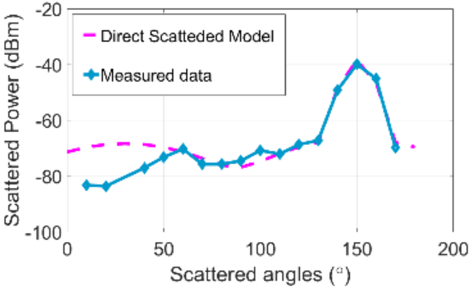
# Scattering Measurements at 140 GHz





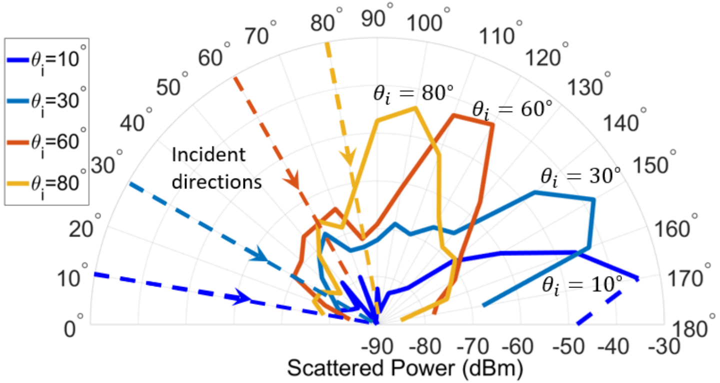


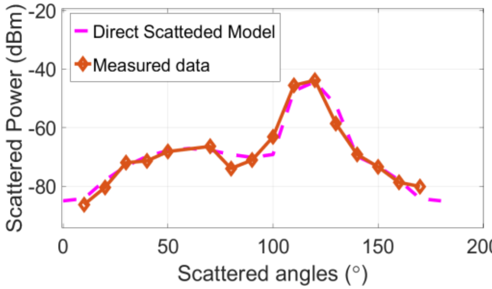

$\theta_i = 10°$



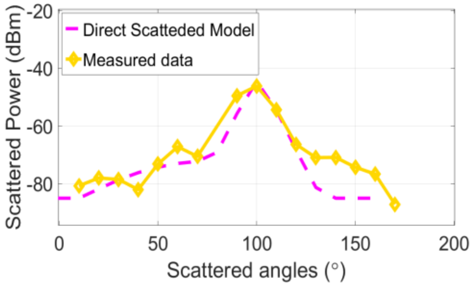

$\theta_i = 30°$

Scatter Pattern at 140 GHz




$\theta_i = 60°$



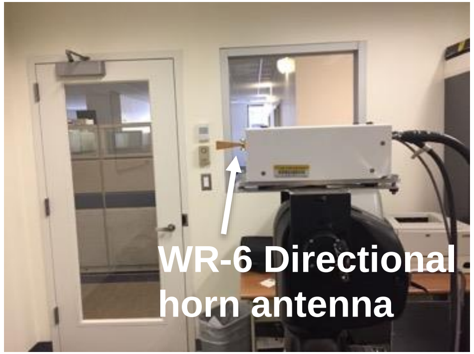

$\theta_i = 80°$

Comparison between measured data and the dual-lobe Directive Scattering (DS) model at 142 GHz [1,26].


[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Alkhateeb, G. C. Trichopoulos, A. Madanayake, S. Mandal, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond (Invited)," IEEE ACCESS, submitted Feb. 2019.

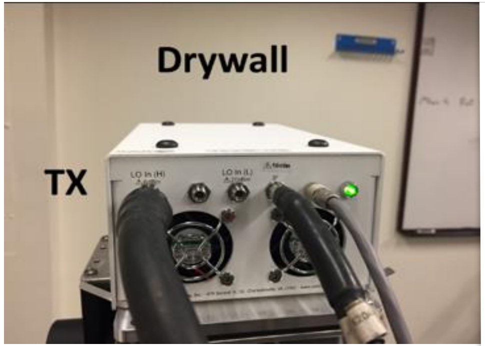
[26] S. Ju et al., "Scattering Mechanisms and Modeling for Terahertz Wireless Communications," 2019 IEEE International Conference on Communications, May. 2019, pp. 1–7.

# Partition Loss Measurements using the 140 GHz channel sounder







[21] Y. Xing and T. S. Rappaport, "Propagation Measurement System and Approach at 140 GHz-Moving to 6G and Above 100 GHz," in IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.
[23] Y. Xing et al., "Verification and calibration of antenna crosspolarization discrimination and penetration loss for millimeter wave communications," in 2018 IEEE 88th Vehicular Technology Conference, Aug. 2018, pp. 1–6.

# Penetration Loss Measurement Results

| 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.

Penetration loss is constant over T-R separation distances for co-polarized antennas.

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

[23] Y. Xing et al., “Verification and calibration of antenna crosspolarization discrimination and penetration loss for millimeter wave communications,” in 2018 IEEE 88th VTC, Aug. 2018, pp. 1–6.

# Conclusion

- New rulemaking report and order (ET Docket 18-21)
    - **21.2 GHz** of unlicensed spectrum.
    - **95 GHz - 3 THz** for experimental licenses.

- Novel use cases for sub-THz and THz: **wireless cognition, imaging, and communications**.

- Early results for precise positioning at sub-THz and THz: **< 10 cm positioning accuracy.**

- Initial scattering and partition loss measurement results at 140 GHz.

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# Industrial Affiliates

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

This work is supported by the NYU WIRELESS Industrial Affiliate Program and National Science Foundation (NSF) (Award Number: 1702967, 1731290 1555332, 1302336, and 1320472).