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

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NYU WIRELESS

for

Federal Communications Commission

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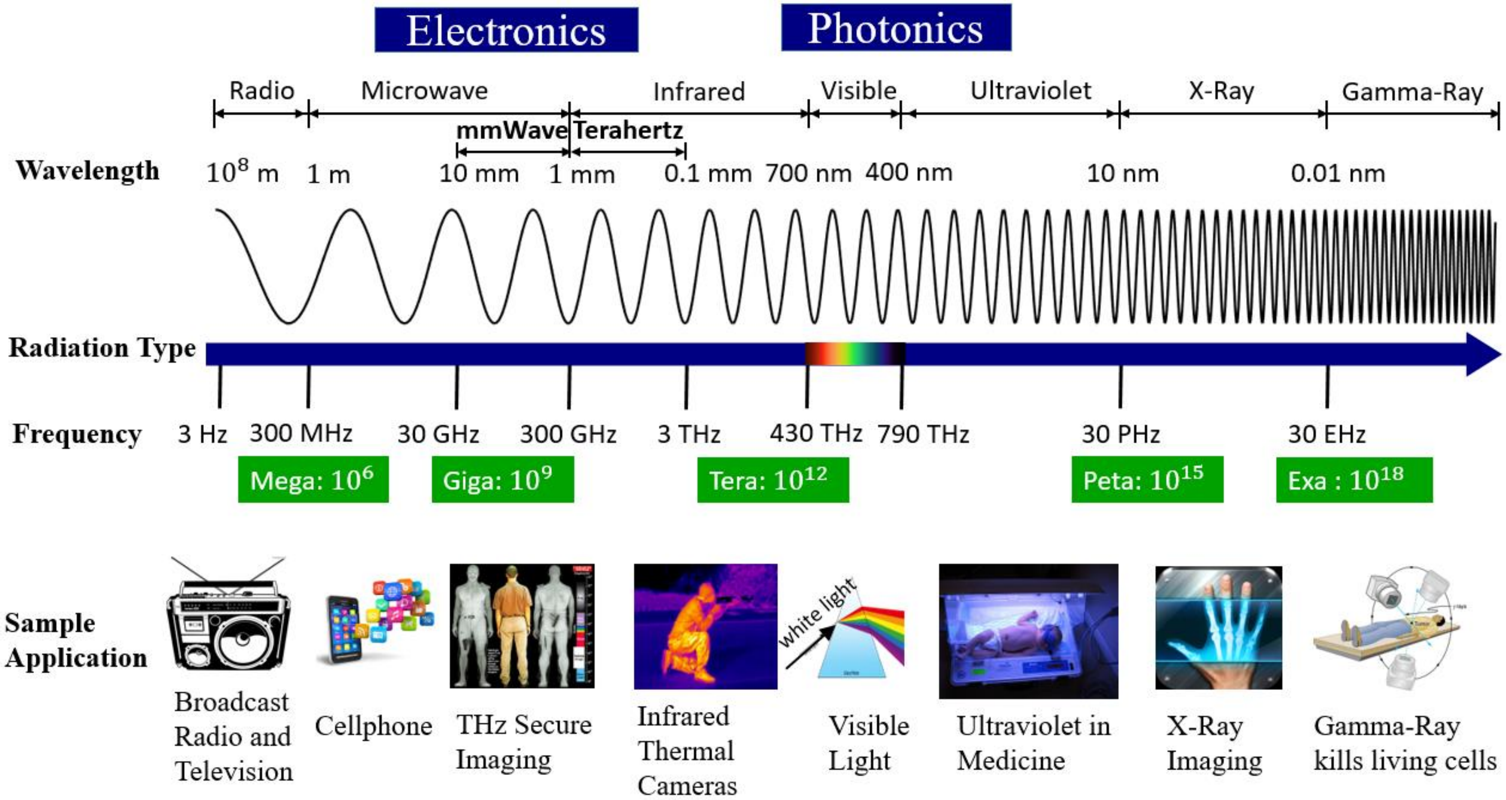
Electromagnetic Spectrum & Applications



[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

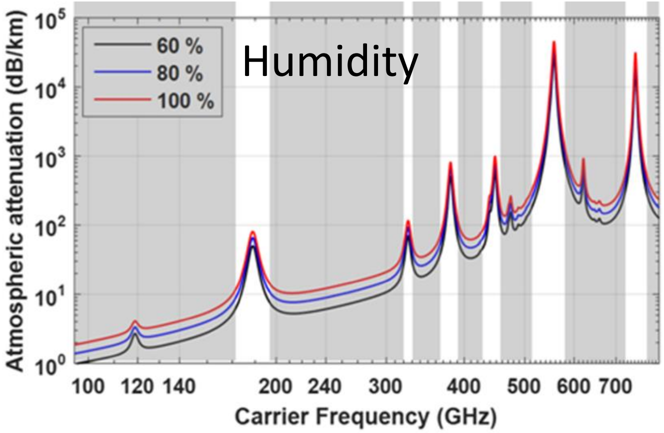
First handheld
phone
(~850 MHz)

2003

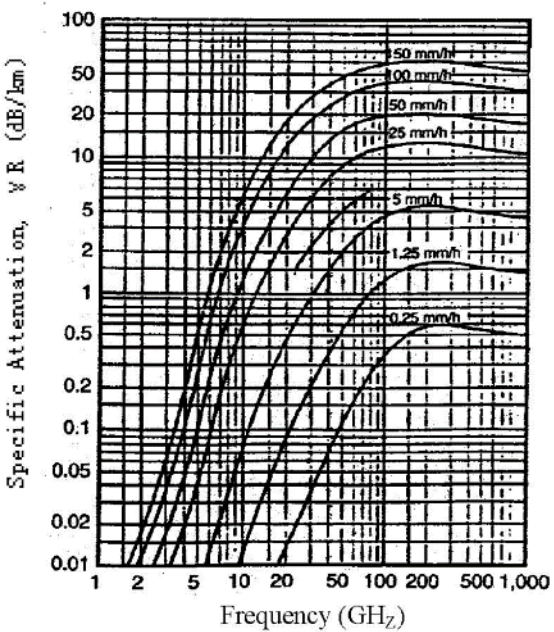
WIFI (~2.4 and
5 GHz)

2019

Foldable Smart
Phone (~3.5 GHz)



Rain Attenuation

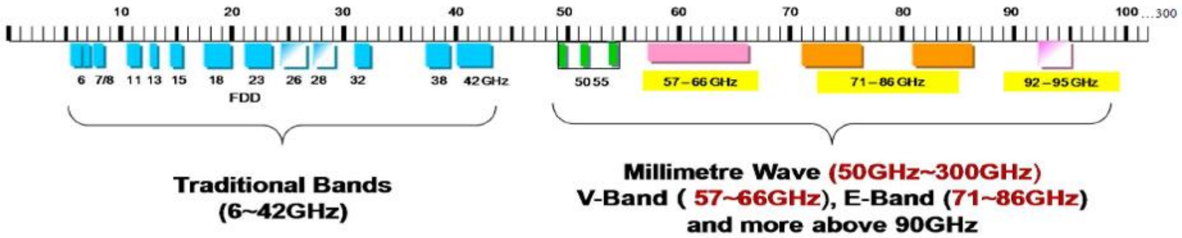


90 Years Just Sub-6 GHz!

[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.

Global 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] Drone Fleet Control [27]
Sensing	Air quality detection [5] Personal health monitoring system [6] Gesture detection and touchless smartphones [7] Explosive detection and gas sensing [8]
Imaging	See in the dark (mmWave Camera) [9] High-definition video resolution radar [10] Terahertz security body scan [11]
Communication	Wireless fiber for backhaul [12] Intra-device radio communication [13] Connectivity in data centers [14] 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.

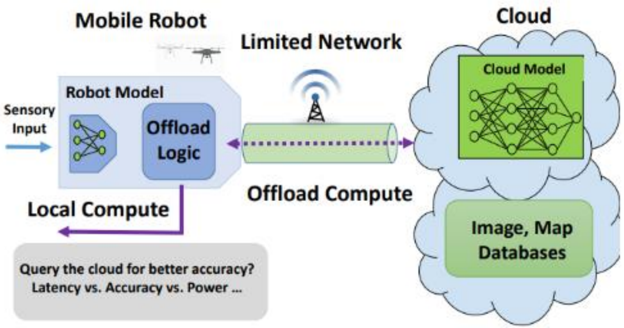
Wireless Cognition

Autonomous cars

Drones Deliver

Robotics

Holographic Imaging and Spatial cognition



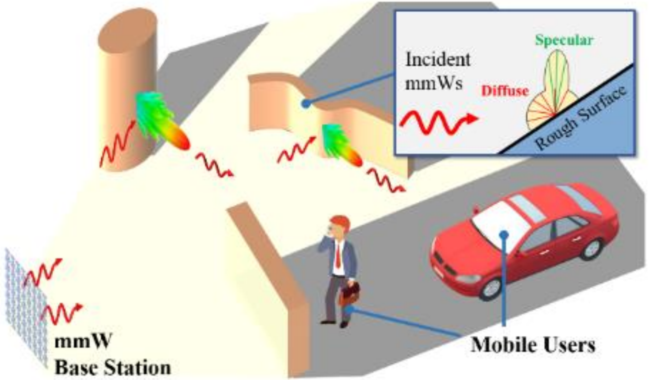
Wireless Cognition (Network Offloading) [17]

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

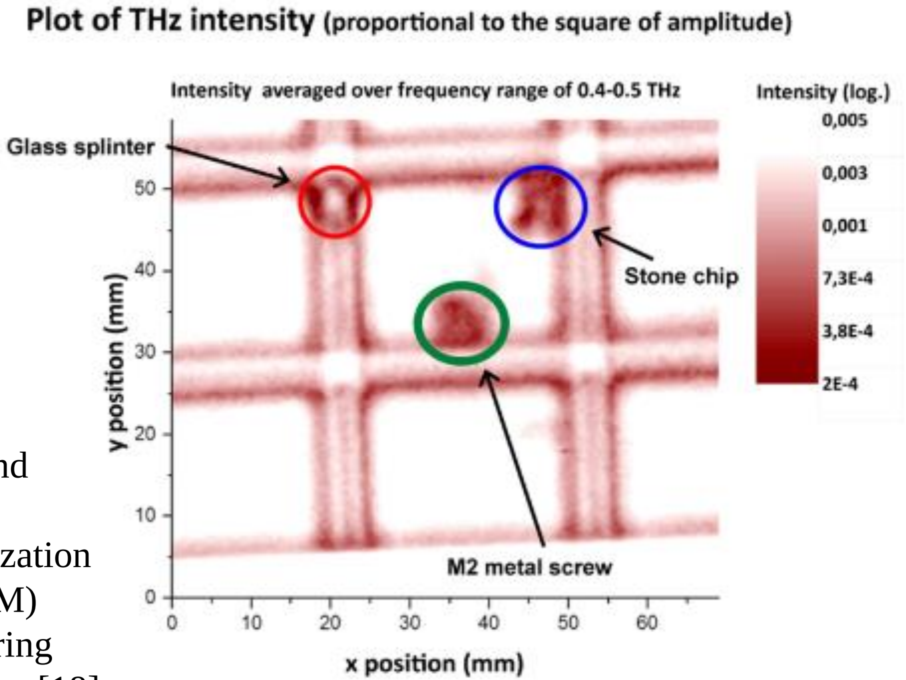
[17] Chinchali S. et. al., Network Offloading Policies for Cloud Robotics: a Learning-based Approach. arXiv preprint arXiv:1902.05703. 2019 Feb 15.

mmWave & THz Imaging

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]



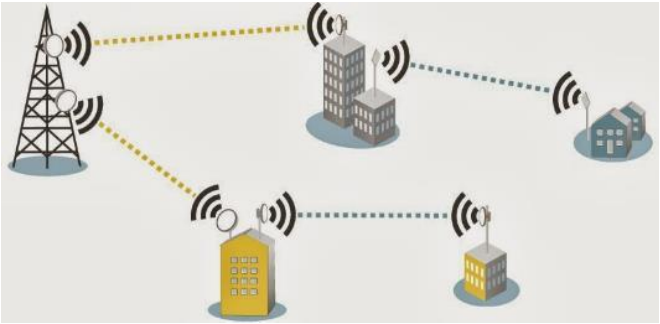
Glass, rock and a metal screw identified in a chocolate bar using THz imaging [17]

[1] http://terasense.com/products/body-scanner/

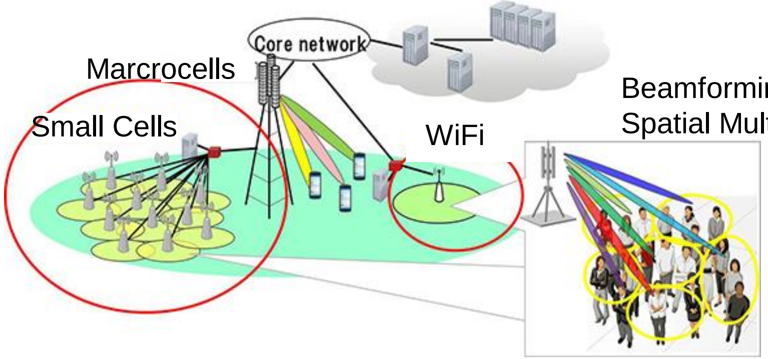
[17] C. Jördens, F. Rutz, M. Koch: Quality Assurance of Chocolate Products with Terahertz Imaging; European Conference on Non-Destructive Testing, 2006 – Poster 67

[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.

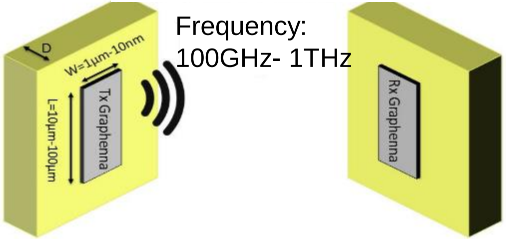
Wireless Communications



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



Mobile Communications [12]



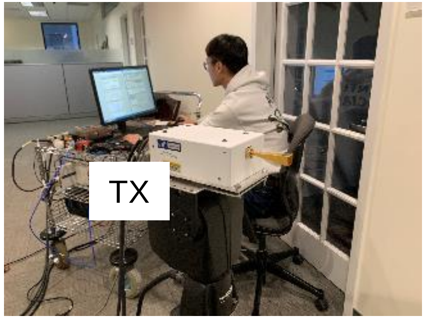
On-chip & chip to chip Terahertz communication links [20]

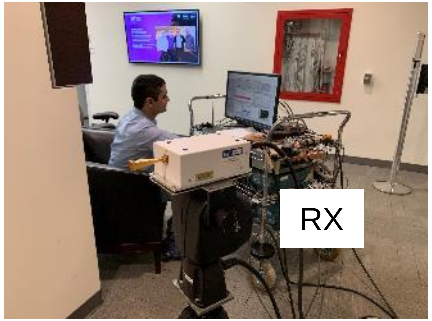
Short-range THz wireless connectivity in data centers [2]

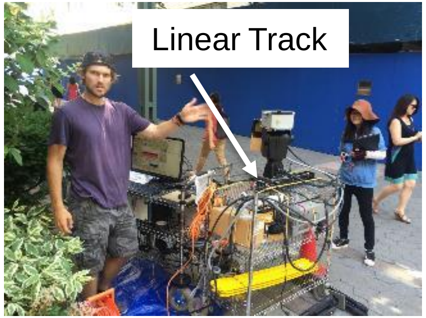
[2] http://terapod-project.eu/wp-content/uploads/2018/03/Re-imagining-data-centres-with-THz.pdf
[3] https://www.rfglobalnet.com/doc/fujitsu-develops-low-power-consumption-technology-for-g-0001
[12] T. S. Rappaport, et al., "Overview of millimeter wave communications for fifth-generation (5G) wireless 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.
[30] S. Sun et al. "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," in *IEEE Comm. Magazine*, vol. 52, no. 12, pp. 110-121, De. 2014.

140 GHz Broadband Channel Sounder at NYU WIRELESS

Conducting measurements [21]







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

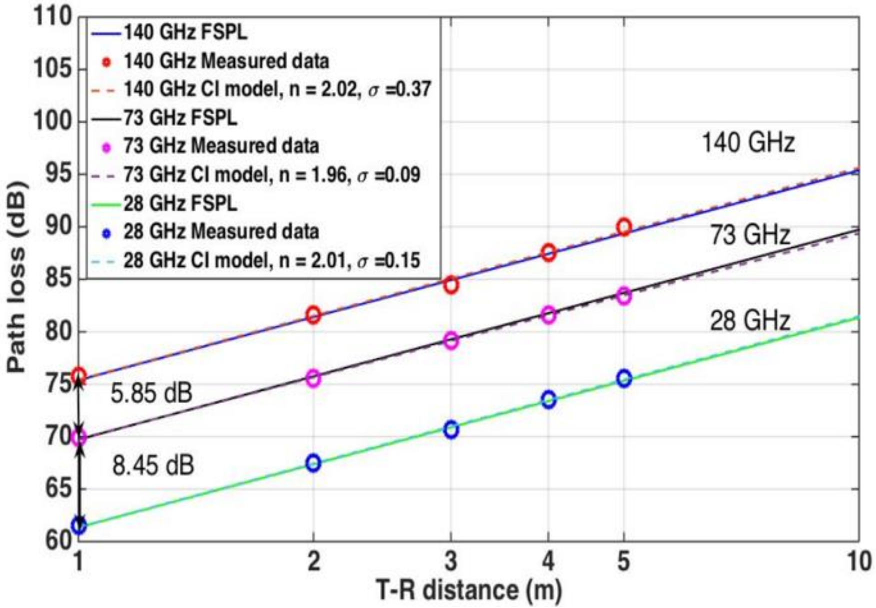
[21] Y. Xing and T. S. Rappaport, "Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz," IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.
[22] https://ieeetv.ieee.org/event-showcase/brooklyn5g2018

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 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 [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

NYU TANDON SCHOOL OF ENGINEERING

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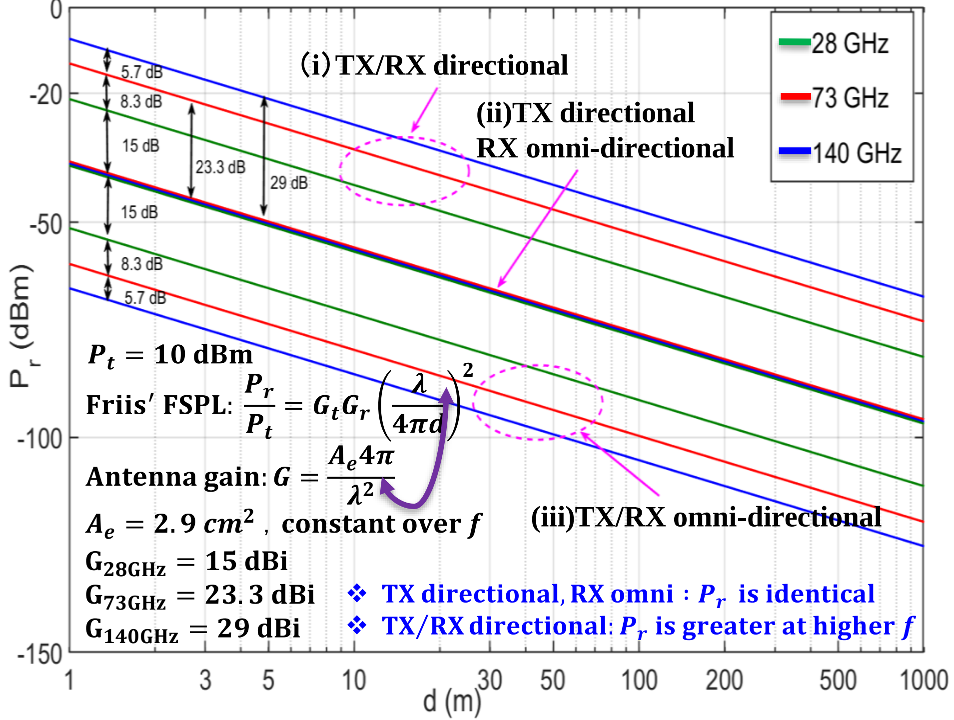
Theoretical Received Power vs. Distances



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

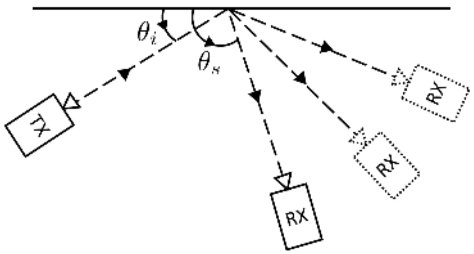
DIRECTIONAL ANTENNAS WITH EQUAL APERTURE HAVE MUCH LESS PATH LOSS AT HIGHER FERQUENCIES ([24] Ch.3 Page 104) !!!

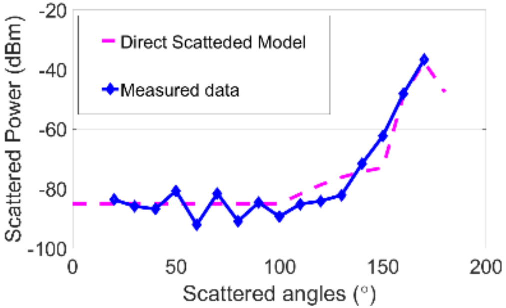
PENETRATION LOSS INCREASES WITH FREQUENCY BUT THE AMOUNT OF LOSS IS DEPENDENT ON THE MATERIAL [21]

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

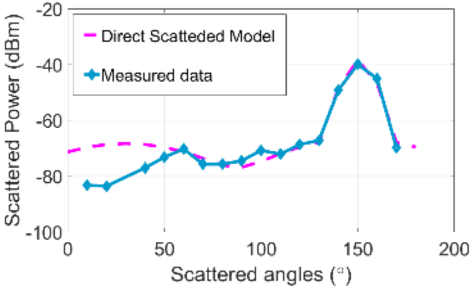
[21] Y. Xing and T. S. Rappaport, "Propagation Measurement System and Approach at 140 GHz-Moving to 6G and Above 100 GHz," in IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

Scattering Measurements at 140 GHz



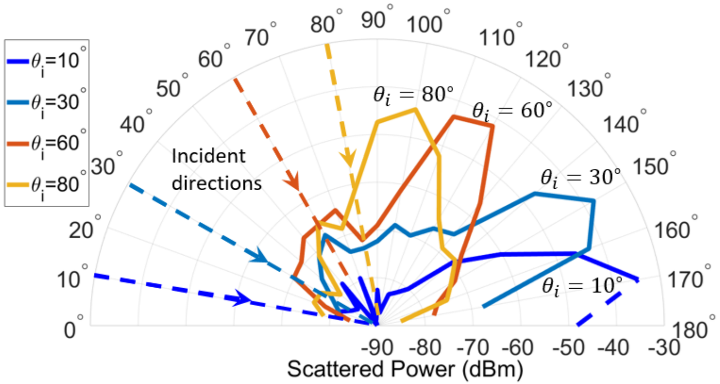


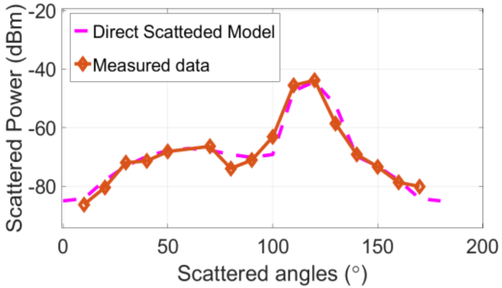
$\theta_i = 10°$



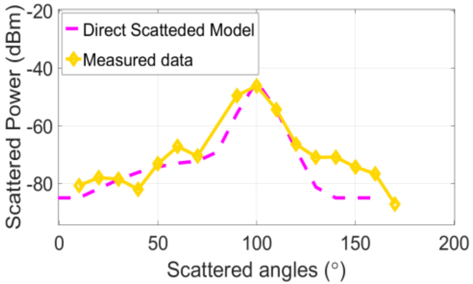
$\theta_i = 30°$

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.

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
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	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**.
- Measurements and channel models are underway at NYU WIRELESS
- This is an important and historic first step at the FCC – perhaps the start of 6G!

References (1/2)

[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.

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[6] X. Teng, Y. Zhang, C. C. Y. Poon and P. Bonato, "Wearable Medical Systems for p-Health," in IEEE Reviews in Biomedical Engineering, vol. 1, pp. 62-74, 2008.

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[11] D. M. Mittleman, “Twenty years of terahertz imaging,” Opt. Express, vol. 26, no. 8, pp. 9417–9431, Apr 2018.

[12] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, “Overview of millimeter wave communications for fifth-generation (5G) wireless networks-with a focus on propagation models,” IEEE Transactions on Antennas and Propagation, vol. 65,no. 12, pp. 6213–6230, Dec. 2017.

[13] V. Petrov et. al., “Ter-ahertz band communications: Applications, research challenges, and standardization activities,” in2016 8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops(ICUMT), Oct 2016, pp. 183–190.

[14] I. F. Akyildiz, J. M. Jornet, and C. Han, “Terahertz band: Next frontier for wireless communications, "Physical Communication, vol. 12, pp.16–32, 2014.

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[17] Christian Jördens, Frank Rutz, Martin 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.

[19] http://terapod-project.eu/wp-content/uploads/2018/03/Re-imagining-data-centres-with-THz.pdf

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

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[27] S. Chinchali, A. Sharma, J. Harrison, A. Elhafsi, D. Kang, E. Pergament, E Cidon, S. Katti, M Pavone, “Network Offloading Policies for Cloud Robotics: a Learning-based Approach”. arXiv preprint arXiv:1902.05703. 2019 Feb 15.

[28] S. Garg, et. al. "Enabling the Next Generation of Mobile Robotics using 5G Wireless," Proceedings of IEEE, in submission.

[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.

[30] S. Sun et al. "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," in IEEE Comm Magazine, vol. 52, no. 12, pp. 110-121, Dec. 2014.