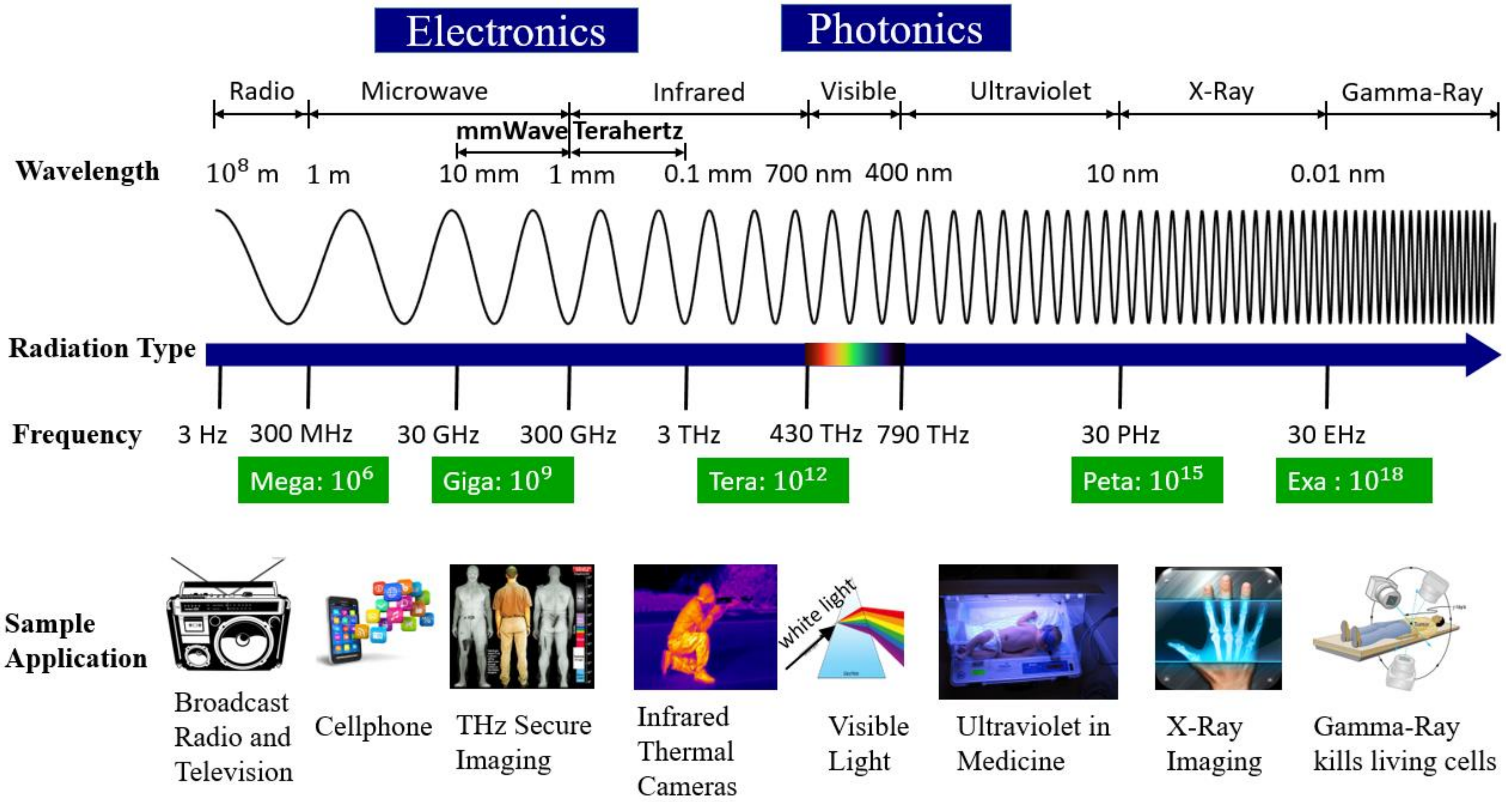
Mini Lecture
NYU WIRELESS
Industrial Affiliates

Spectrum Frontiers: Terahertz

Prof. Ted Rappaport
NYU WIRELESS

February 17, 2021

Radio Spectrum Usage



[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, Vol. 7, No. 7, June 2019 https://ieeexplore.ieee.org/document/8732419

New Consumer Usage above 100 GHz

FCC ET DOCKET 18-21 SPECTRUM HORIZONS

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

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

FCC Approved on March 15th 2019

Spectrum Horizons Experimental Radio Licenses

- Frequency within **95 GHz to 3 THz**.
- No interference protection from pre-allocated services.
- Interference analysis before license grant.
- Rules on Licensed spectrum deferred until sufficient technical and market data is obtained (NYU Thrust area).

http://mmwavecoalition.org/wp-content/uploads/2019/02/DOC-356297A1-FCC-Report-Order.pdf
https://www.fcc.gov/document/fcc-opens-spectrum-horizons-new-services-technologies-0

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

Only 16 % of the available spectrum (116-246 GHz), primarily due to the forbidden bands in US246

Applications Above 100 GHz

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.

The Human Brain & Human Intelligence

How powerful is the human brain?

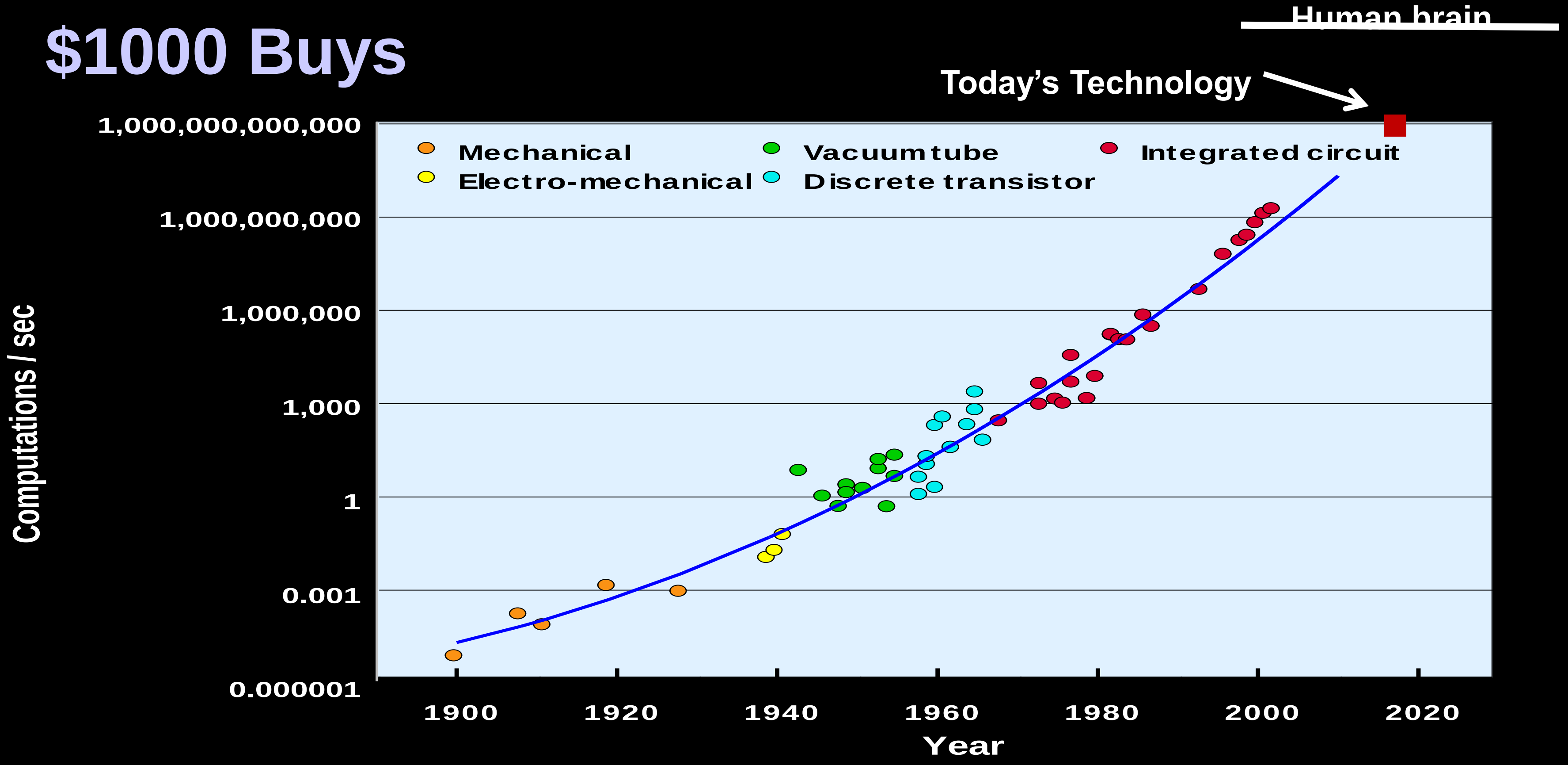
- 100 billion neurons
  Fire 200 times per second (5 milliseconds)

- Each neuron connected to 1000 others

- Speed = $(10^{11}) \times (200) \times (10^{3}) = 20\times10^{15}$
- (20 petaflops)/second = 20,000 Tbps

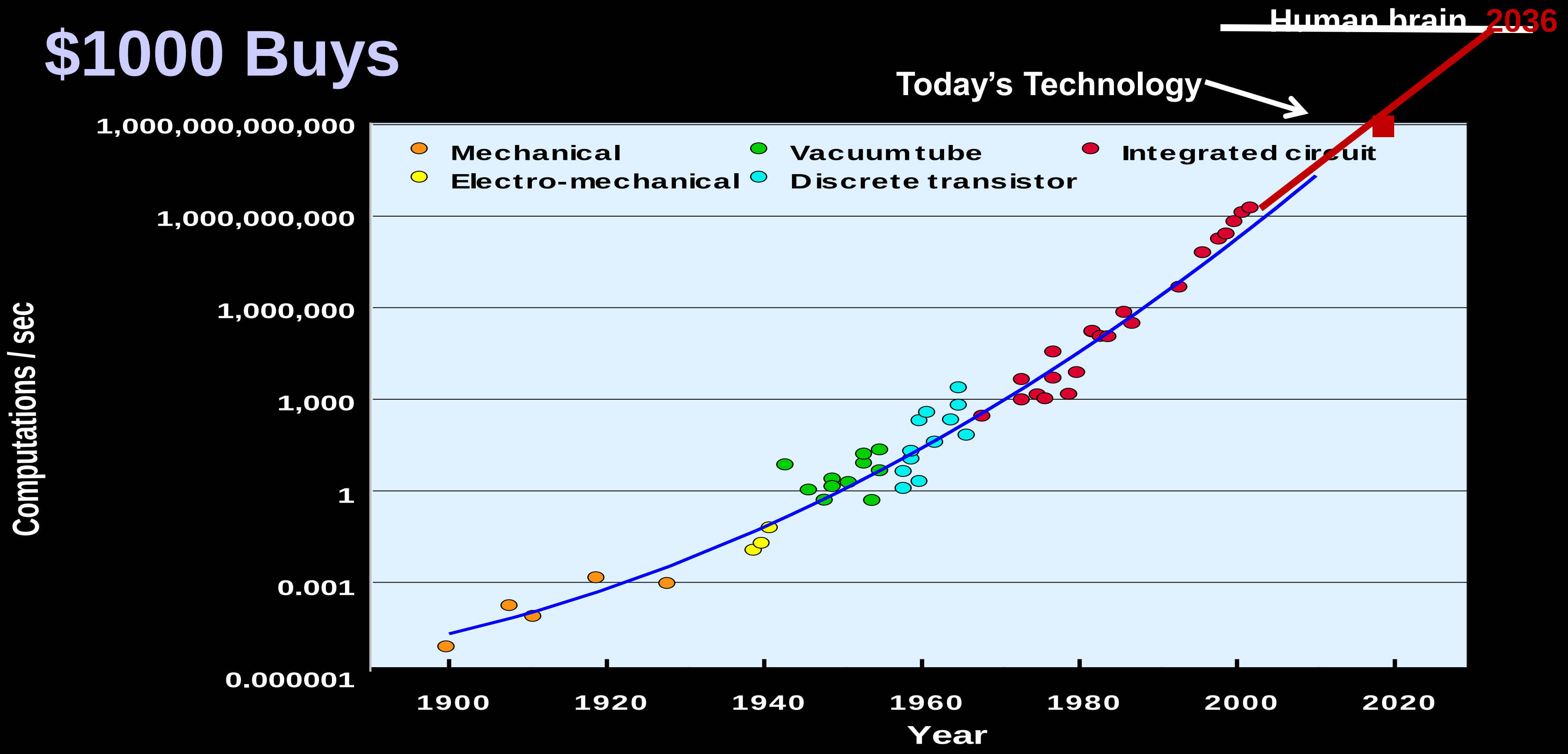
- Each neuron has write access to 1000 bits
  Storage = $(10^{11}) \times (10^{3}) = 10^{14} = 100\times10^{6}\times10^{6}$
  =100 million megabytes = 100 terabytes

$1000 Buys



after Kurzweil, 1999 & Moravec, 1998

$1000 Buys



after Kurzweil, 1999 & Moravec, 1998

Can we remote the Human Brain?

Wireless in 2036: 6G or 7G?

- 10 GHz RF User Channels (10^{10}) Hz
- 1024 QAM (10 bits/second)
- 1000 X Channel/Antenna Capacity (Beyond M-MIMO)
- PHY: 100 Terabytes/second (0.5% of human brain)

- 100 GHz channels: 1 Petabyte/second (5% of human brain)
- Other wireless breakthroughs may increase link speed

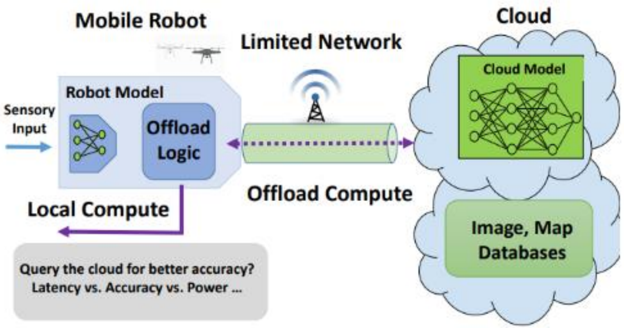
Applications Above 100 GHz

Autonomous cars

Drones Deliver

Robotics

Holographic Imaging and Spatial cognition



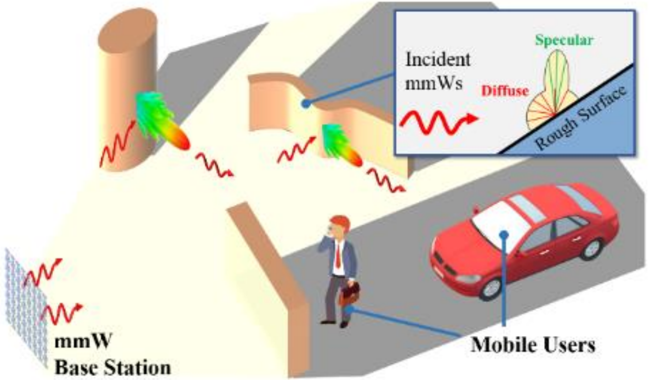
Wireless Cognition （Network Offloading） [17]

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

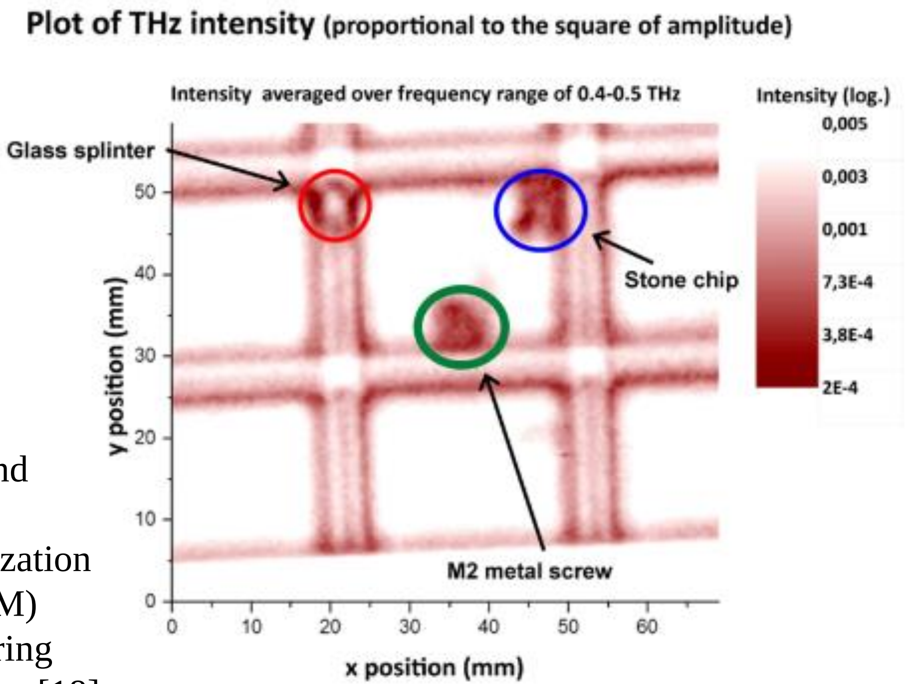
[17] Chinchali S. et. al., Network Offloading Policies for Cloud Robotics: a Learning-based Approach. arXiv preprint arXiv:1902.05703. 2019 Feb 15.

Applications Above 100 GHz

Body scanner using THz imaging to detect explosives [1]



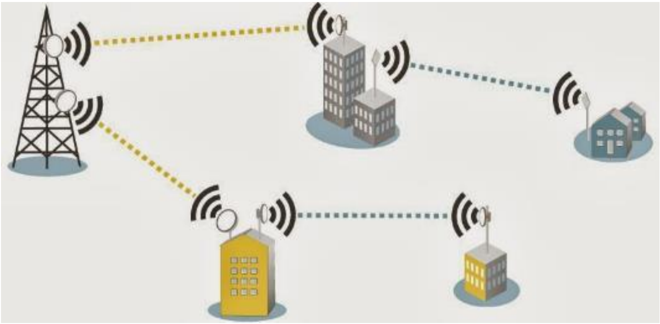
mmWave imaging and communications for Simultaneous Localization And Mapping (SLAM) exploiting the scattering properties at mmWave [18]



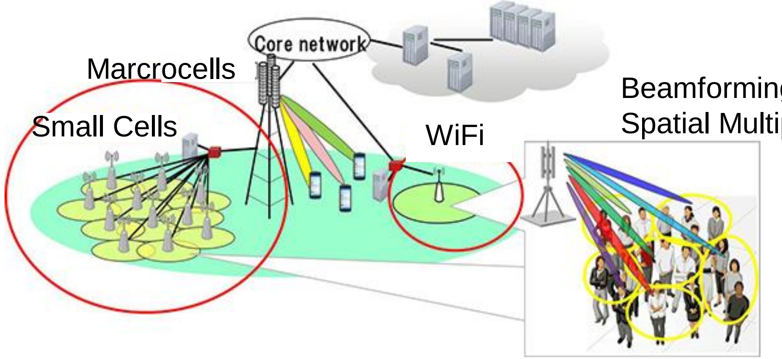
Glass, rock and a metal screw identified in a chocolate bar using THz imaging [17]

[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.

Applications Above 100 GHz

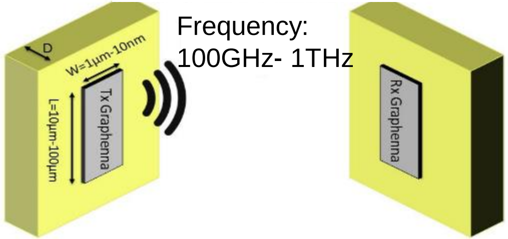


100 Gbps ~ 1 Tbps backhaul links over rooftops [12]



Mobile Communications [12]

Range: 10mm-1mm



Frequency:
100GHz- 1THz

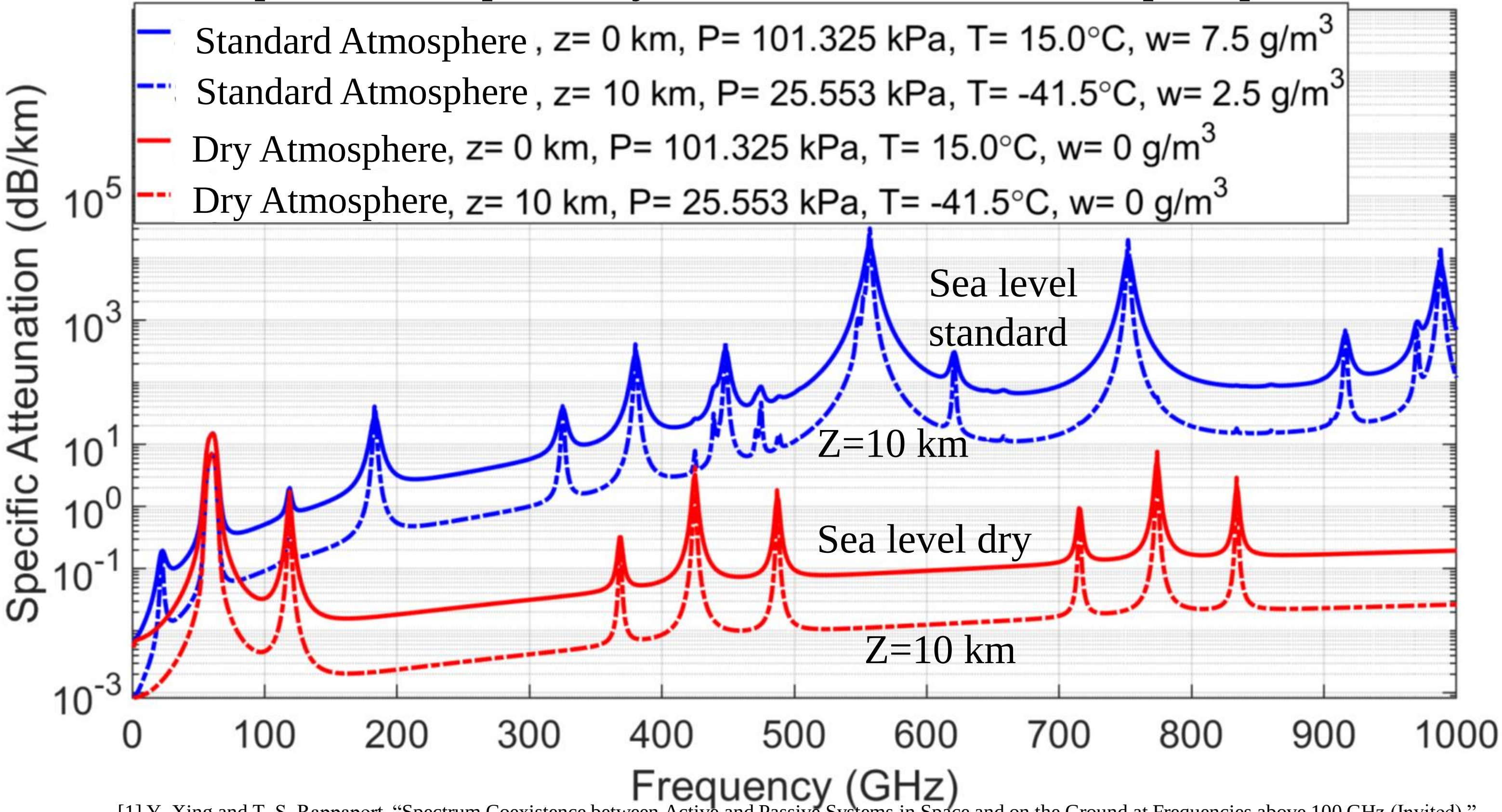
On-chip & chip to chip Terahertz communication links [20]

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.

Propagation Fundamentals above 100 GHz on earth (1/2)

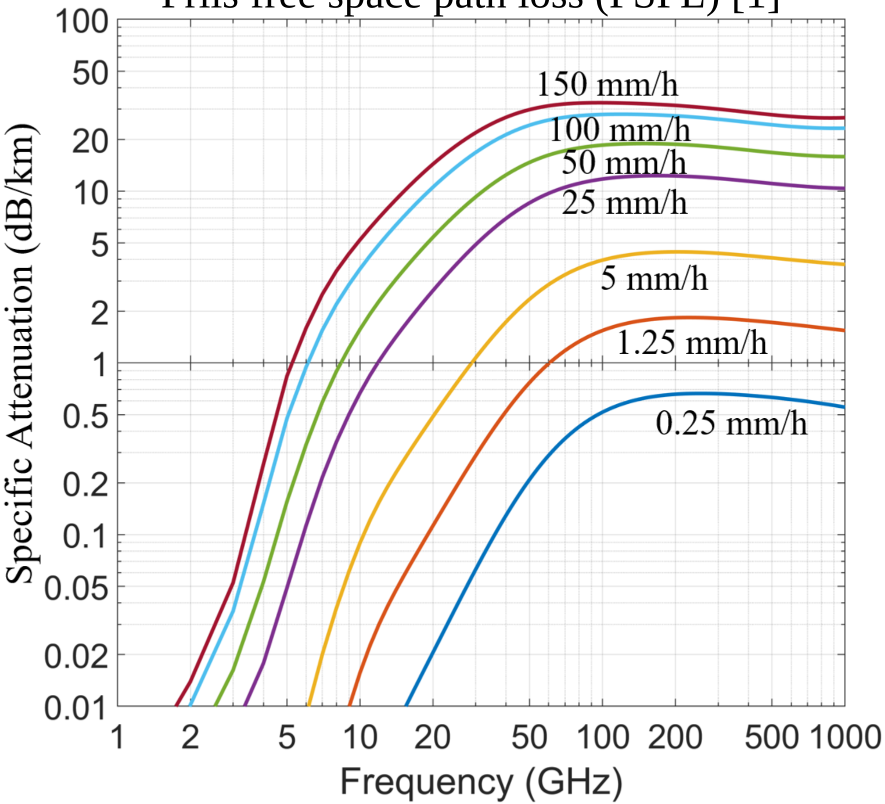
Atmospheric absorption beyond the natural Friis free space path loss [1]



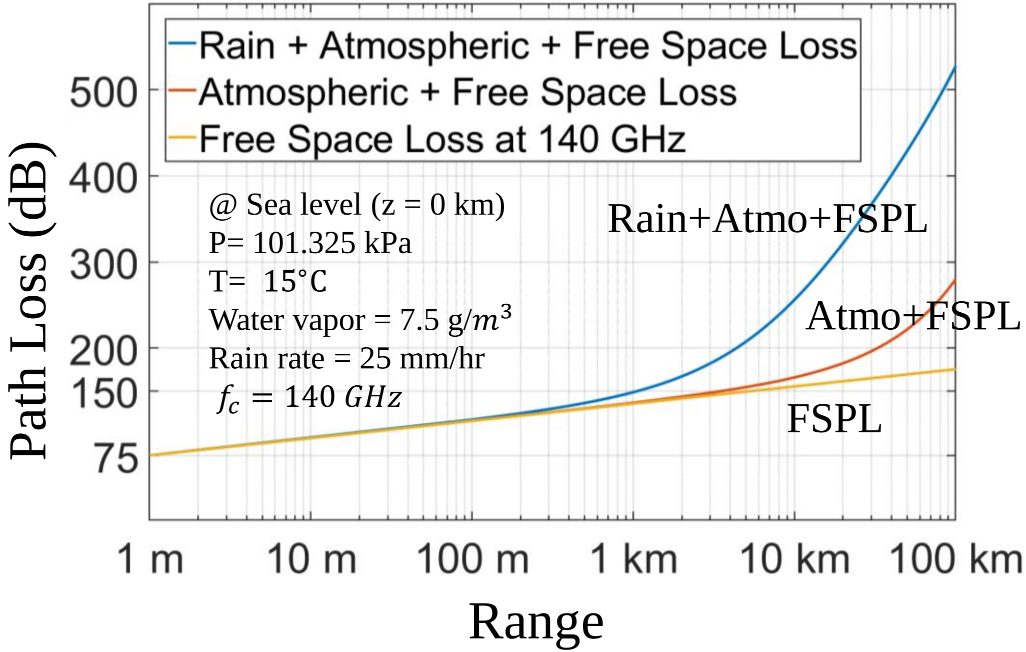
[1] Y. Xing and T. S. Rappaport, "Spectrum Coexistence between Active and Passive Systems in Space and on the Ground at Frequencies above 100 GHz (Invited)," in submission to IEEE Communication Letters, Feb. 2021, pp. 1-5.

Propagation Fundamentals above 100 GHz on earth (2/2)

Rain Attenuation beyond the natural Friis free space path loss (FSPL) [1]



Total Path Loss including FSPL, rain attenuation, and atmospheric absorption [1]



Little impact on short ranges (e.g., d ≤ 100 m), huge impact on large distances (e.g., d ≥ 1 km)

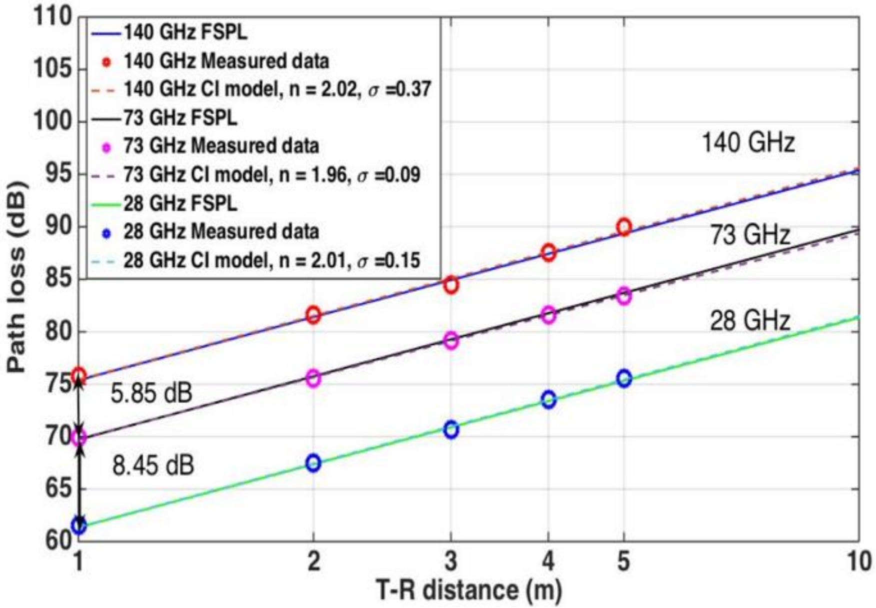
[1] Y. Xing and T. S. Rappaport, "Spectrum Coexistence between Active and Passive Systems in Space and on the Ground at Frequencies above 100 GHz (Invited)," in submission to IEEE Communication Letters, Feb. 2021, pp. 1-5.

Free Space Path Loss: 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

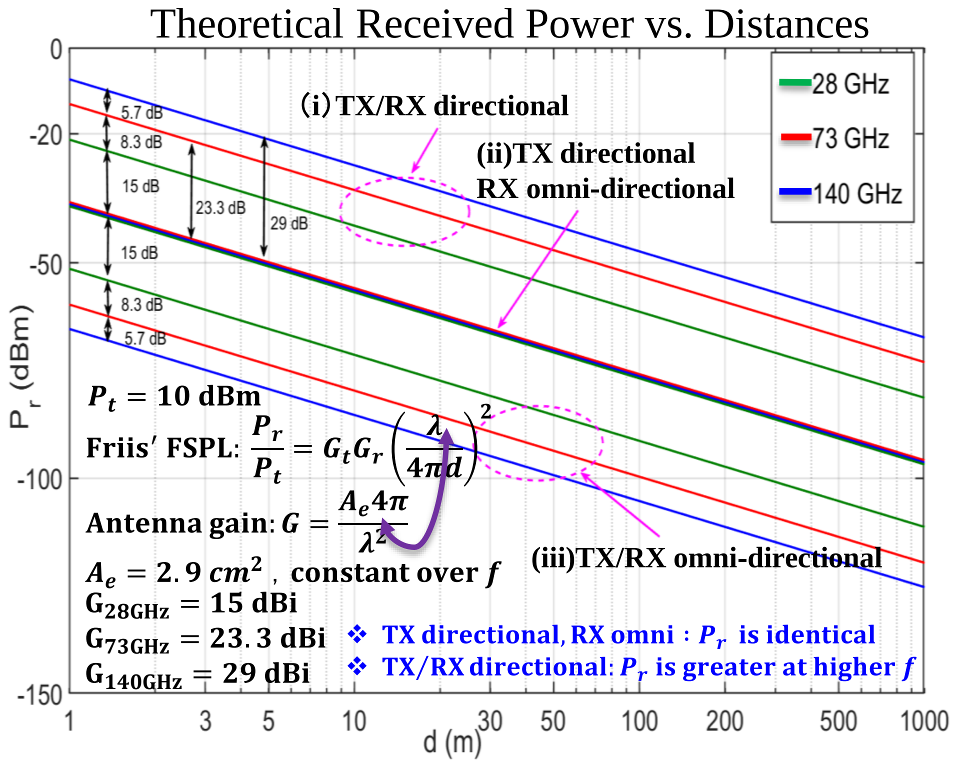
FSPL verifications following the proposed method at 28, 73, and 140 GHz [23] (after removing antenna gains)



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.

Penetration Loss: 28, 73 & 140 GHz



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

Penetration Loss at 28, 73, and 140 GHz

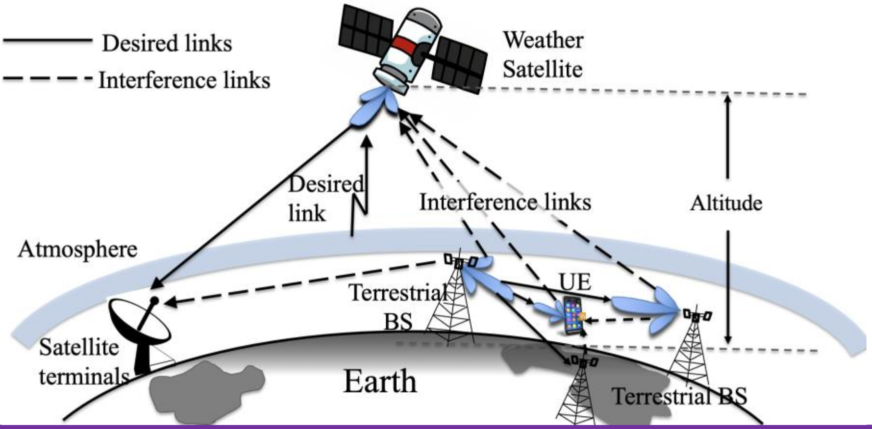
Frequency (GHz)	Material Under Test	Thickness (cm)	Penetration Loss (dB)
28	Clear glass No.1	1.2	3.60
	Clear glass No.2	1.2	3.90
	Drywall No.1	38.1	6.80
73	Clear glass No.3	0.6	7.70
	Clear glass No.4	0.6	7.10
	Drywall No.2	14.5	10.06
140	Clear glass No.3	0.6	8.24
	Clear glass No.4	0.6	9.07
	Drywall No.2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

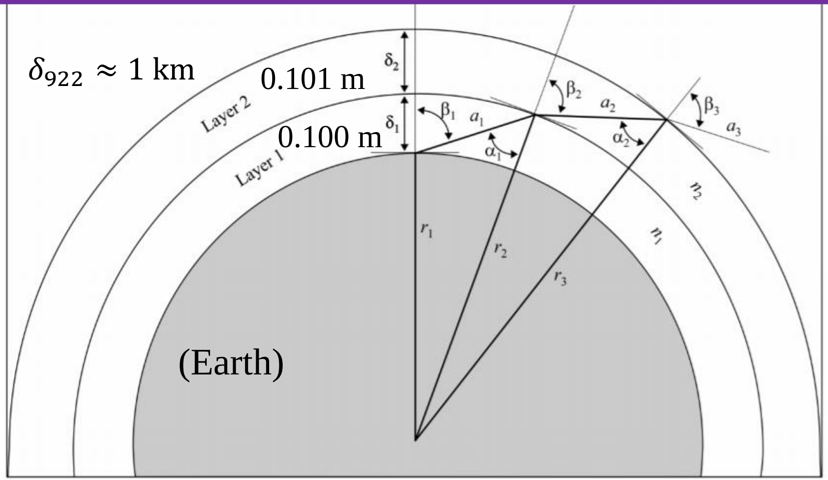
PENETRATION LOSS INCREASES WITH FREQUENCY BUT THE AMOUNT OF LOSS IS DEPENDENT ON THE MATERIAL [21

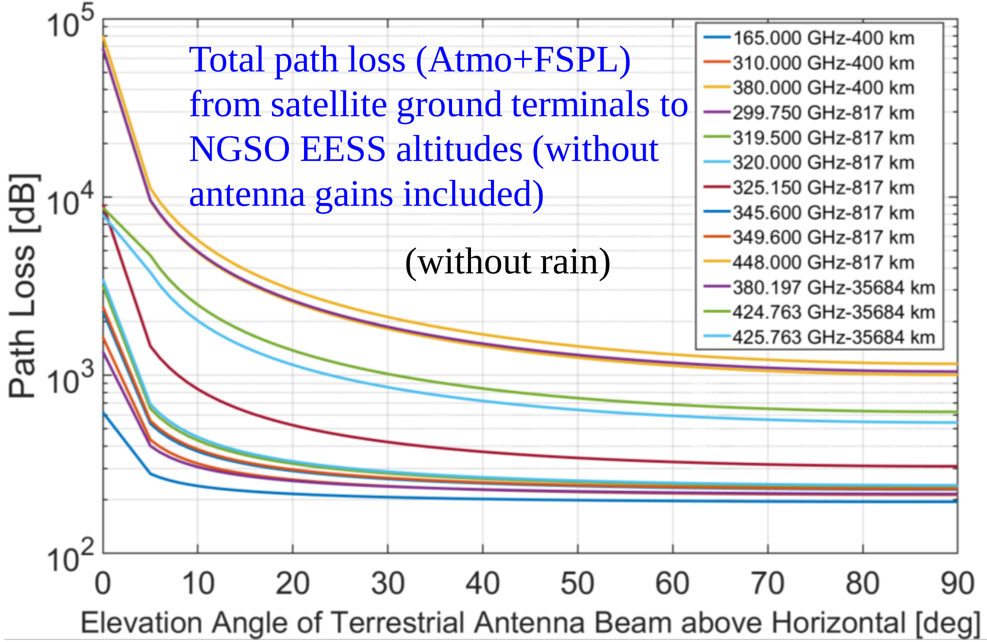
[24] T. S. Rappaport, et. al., "Millimeter Wave Wireless Communications," Pearson/Prentice Hall c. 2015.

[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.

Earth-Space Path Loss (Slant Paths)







$$A_{gas} = \sum_{i=1}^{i_{max}} a_i \gamma_i \ (dB)$$

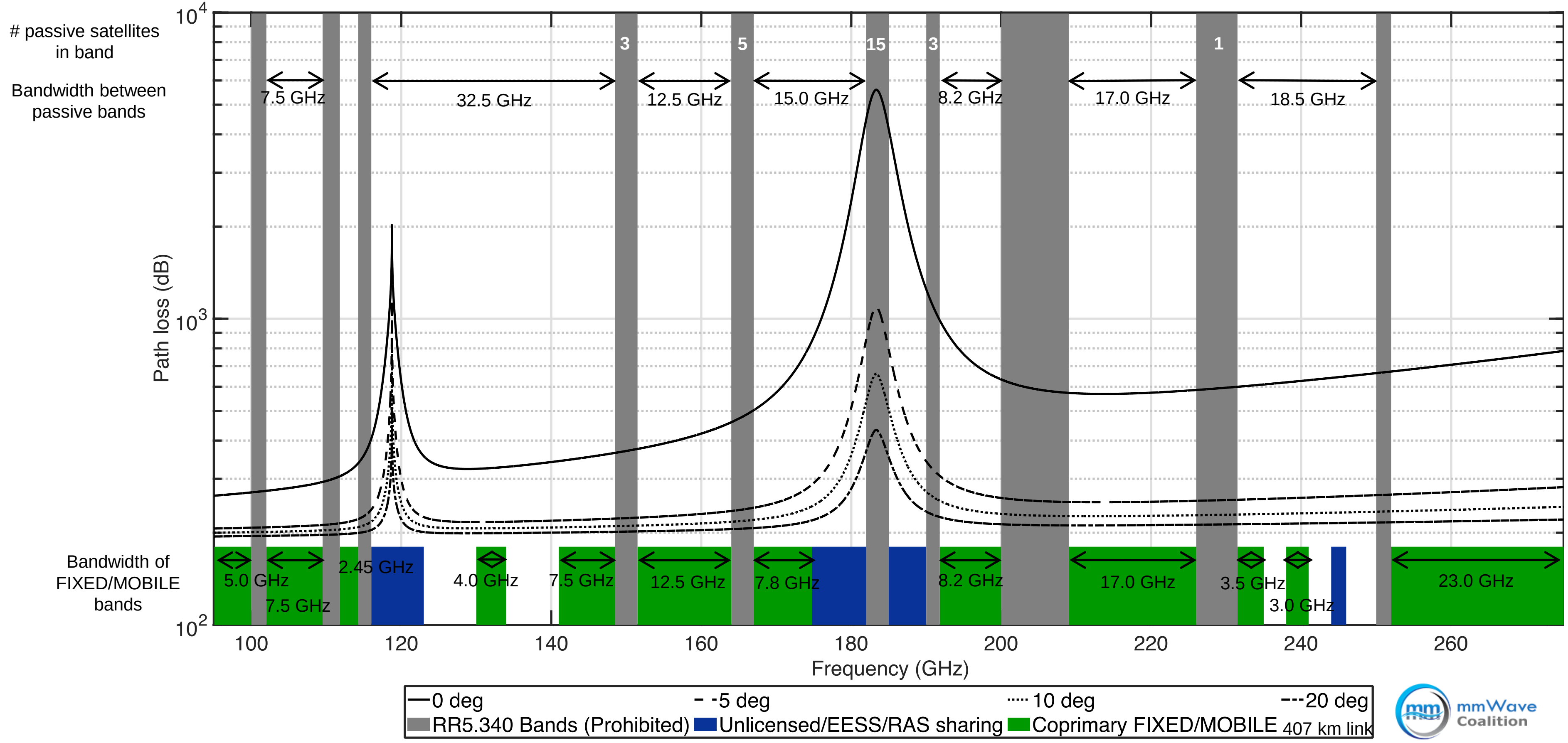
a_i : the path length (km) through the i^{th} layer

γ_i : the specific attenuation (dB/km) of the i^{th} layer

$$\delta_i = 0.0001 \exp\left\{\frac{i-1}{100}\right\} \text{ (km)}$$

$$Zmax = \sum_{i=1}^{922} \delta_i \approx 100\ km$$

[1] Y. Xing and T. S. Rappaport, "Spectrum Coexistence between Active and Passive Systems in Space and on the Ground at Frequencies above 100 GHz (Invited)," in submission to IEEE Communication Letters, Feb. 2021, pp. 1-5.



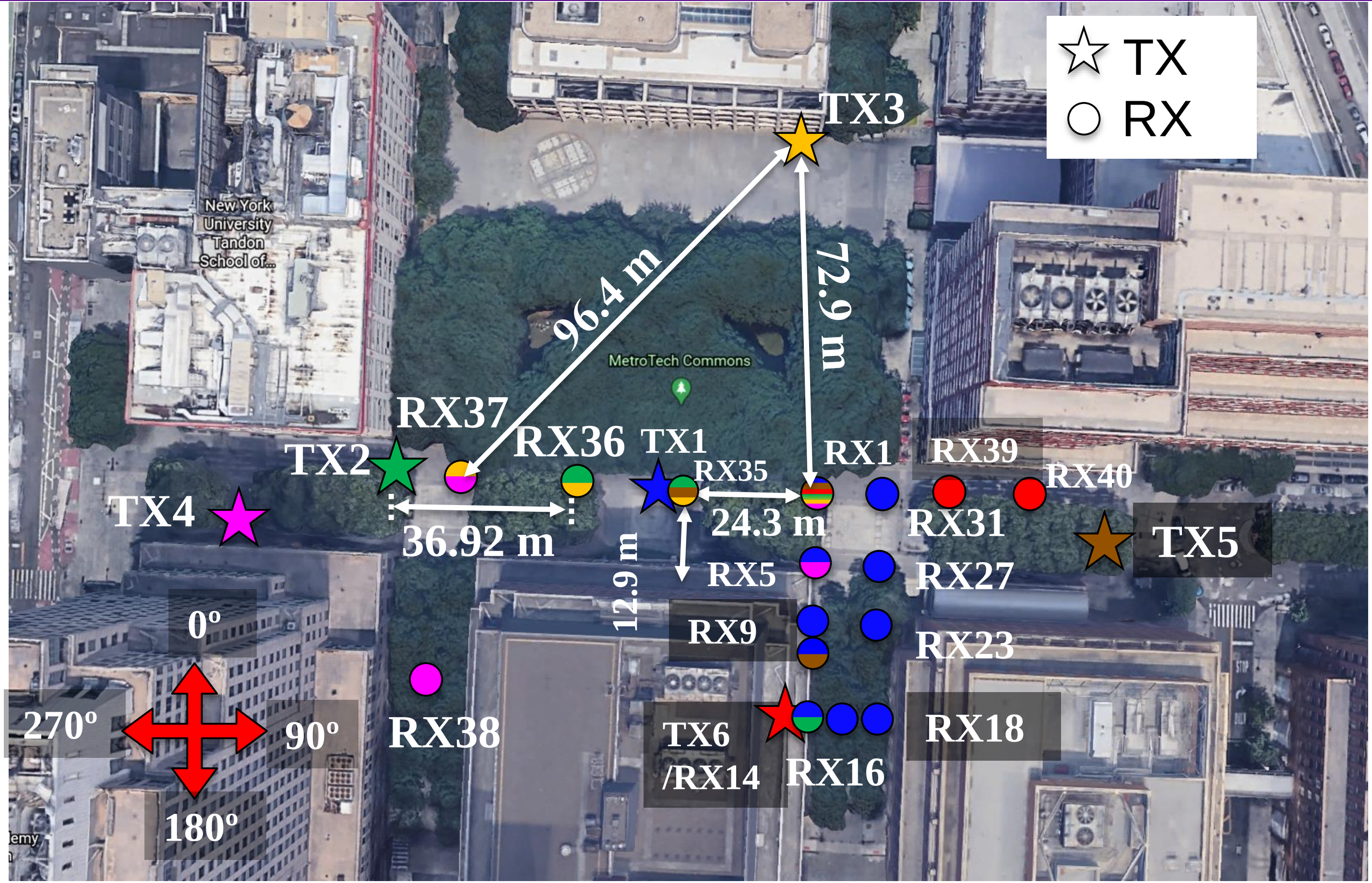
Key ITU spectrum allocation above 100 GHz with RR5.340 prohibited bands, unlicensed/EESS/RAS sharing bands, and coprimary fixed/mobile bands, from Millimeter Wave Coalition.

[1] Y. Xing and T. S. Rappaport, "Spectrum Coexistence between Active and Passive Systems in Space and on the Ground at Frequencies above 100 GHz (Invited)," in submission to IEEE Communication Letters, Feb. 2021, pp.1-5.
[2] M. J. Marcus, J. M. Jornet, and X. C. Roman, "Opening Spectrum > 95 GHz for Practical Use: Recent Actions on Sharing and Regulatory Issues," in submission to 2021 IEEE International Microwave Symposium (IMS), Feb 2021, pp. 1–4.

NYU WIRELESS Research

- Extensive indoor/outdoor propagation measurements at 142 GHz, all data will be made available to NYU WIRELESS Industrial Affiliates
- 20-178 m TR distances, 1 GHz RF bandwidth, 20 PDPs averaging, 53 TX-RX locations, LOS and NLOS, over 10, 000 PDPs in total
- Urban Microcell, Small Cell, and Coordinated Multi-Point (CoMP)
- Surrogate Satellite (Rooftop) Measurements for terrestrial interference- **foundational knowledge and new field of work**
- Channel modeling at frequencies above 100 GHz

140 GHz Base Station Propagation Measurements in Urban Microcell



- Distance: 20-180 m
- 6 TX locations
- 40 RX locations
- 53 TX-RX pairs
- 32 LOS + 21 NLOS
- 45 rotations/sweep separated by HPBW in the azimuth plane
- 3 different RX elevation angles
- Over 10,000 PDPs in total

SII: 140 GHz Surrogate Satellite Measurements

TX at 1.5 m high above the ground, working as a mobile terminal, transmitting signals in every direction

View from the ground to the roof

RX on the roof, emulating a passive receiver at the satellite, search every direction to capture any signal

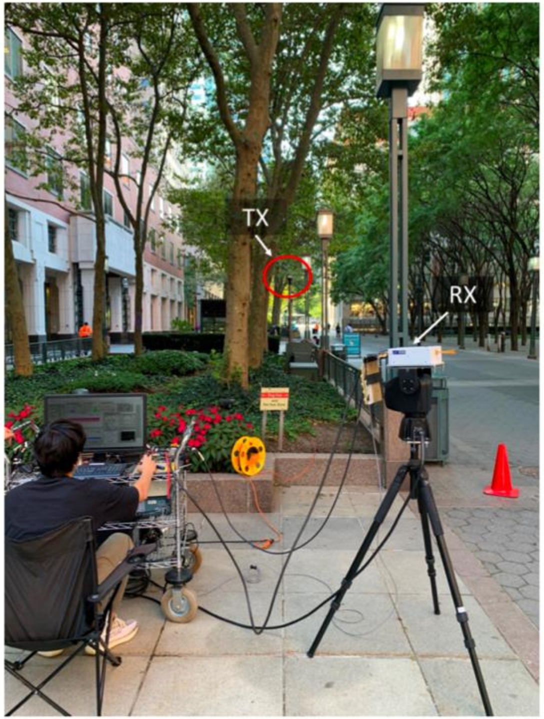
[1] Y. Xing and T. S. Rappaport, "Propagation Measurements and Path Loss models for sub-THz in Urban Microcells," in IEEE International Conference on Communications (ICC), Virtual/Montreal, pp.1-6, June 2021.

IRIS: Terahertz Study Project @ 140 GHz

Microcell rooftop tall BS
(38.2 m above the ground)

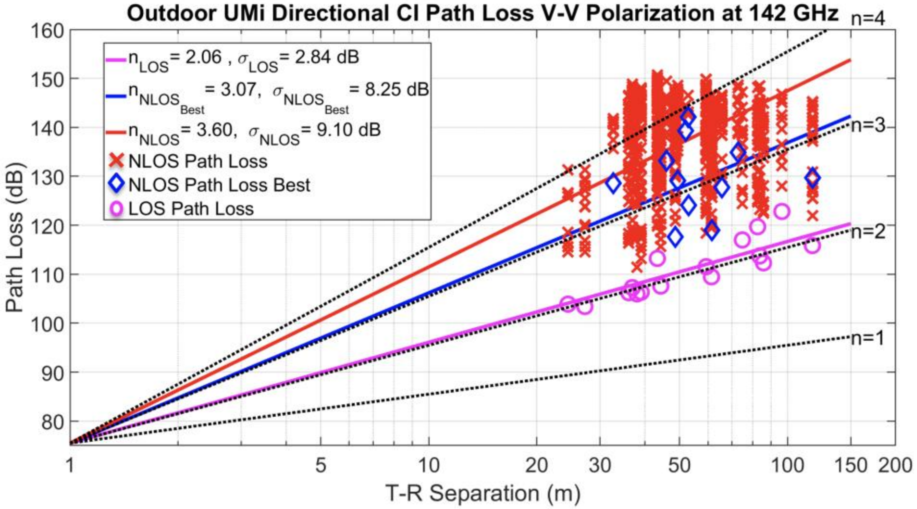
Small-cell lamppost BS
(4.0 m above the ground)

UE at 1.5 m ht

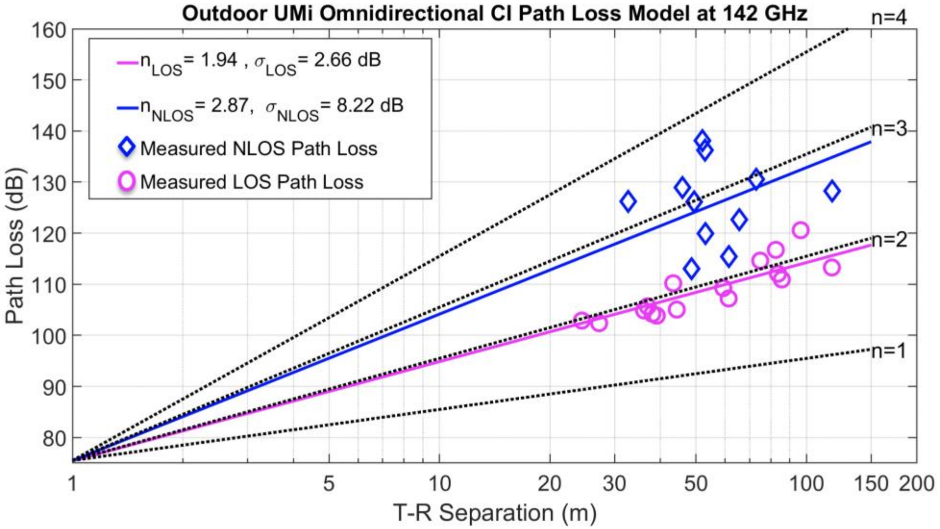


140 GHz Outdoor Urban Microcell Path Loss

Urban UMi 142 GHz directional path loss scatter plot and outdoor directional CI path loss model for both LOS and NLOS scenarios using 27 dBi gain, 8° HPBW horn antennas at both the TX and RX (without antenna gains included for path loss calculations).



Urban UMi 142 GHz omnidirectional path loss data with CI path loss model (without antenna gains included for path loss calculations) for both LOS and NLOS scenarios.



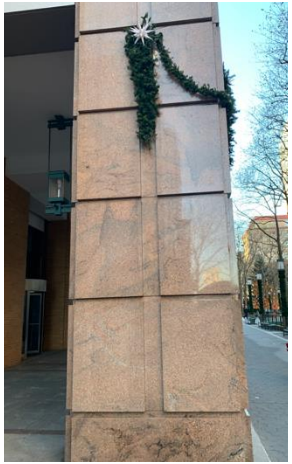
[1] Y. Xing and T. S. Rappaport, "Propagation Measurements and Path Loss models for sub-THz in Urban Microcells," in IEEE International Conference on Communications (ICC), Virtual/Montreal, pp.1-6, June 2021.

140 GHz Base Station Propagation Measurements in Urban Microcell

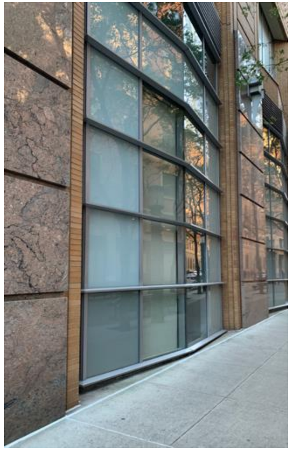
Lampposts and trees

Concrete building corners

Glass wall/window



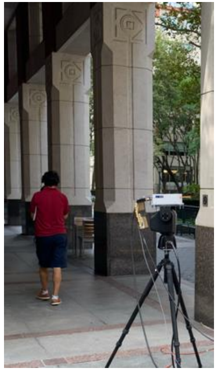
Marble pillars



Marble walls and glass walls

Trees

Pedestrians

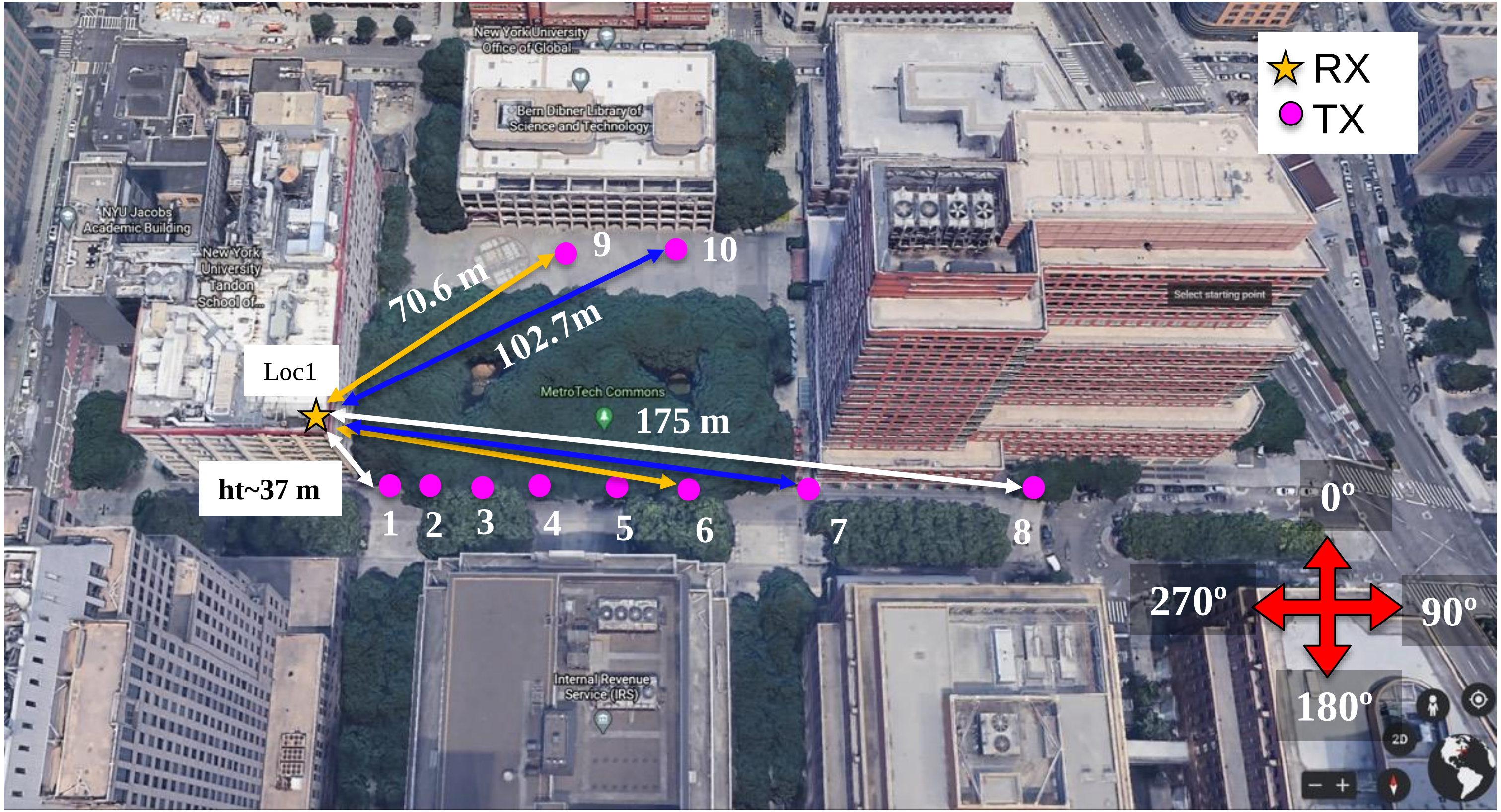


Concrete pillars with corridors

Trees and foliage

Bench and lampposts with holiday cover

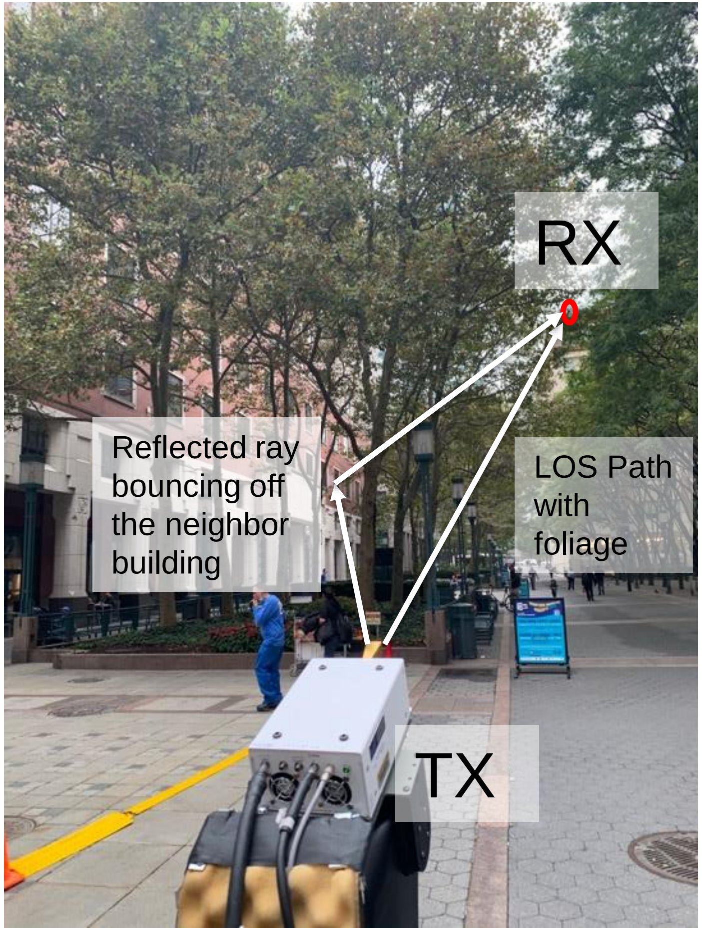
2. Antenna patterns key for interference mitigation



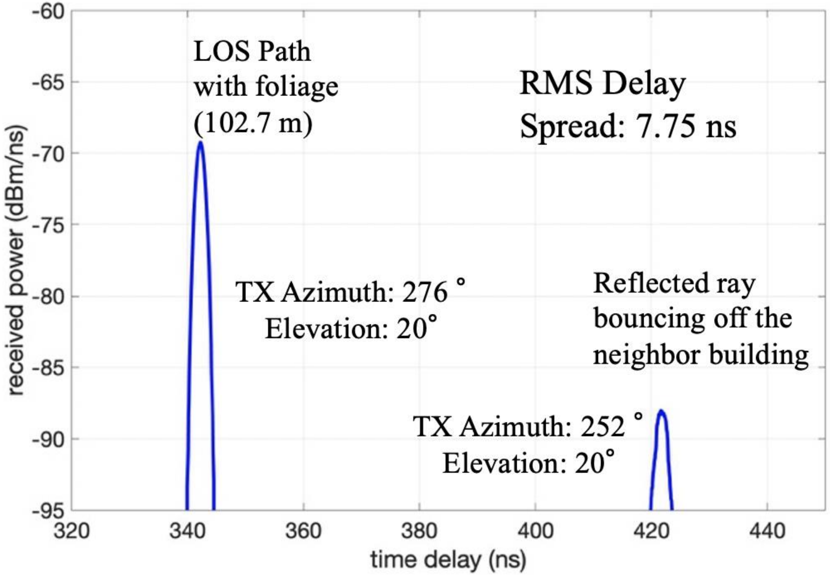
- 6 MetroTech Roof top, Brooklyn
- RX Height: 37.2 m
- TX Height: 1.5 m
- 10 ground locations
- Elevation angle from 10-80˚
- Comparisons to foliage locations
- Measure reflected/scattered power from neighbor buildings

[1] Y. Xing and T. S. Rappaport, "Propagation Measurements and Path Loss models for sub-THz in Urban Microcells," in IEEE International Conference on Communications (ICC), Virtual/Montreal, pp.1-6, June 2021.

140 GHz Surrogate Satellite Measurement



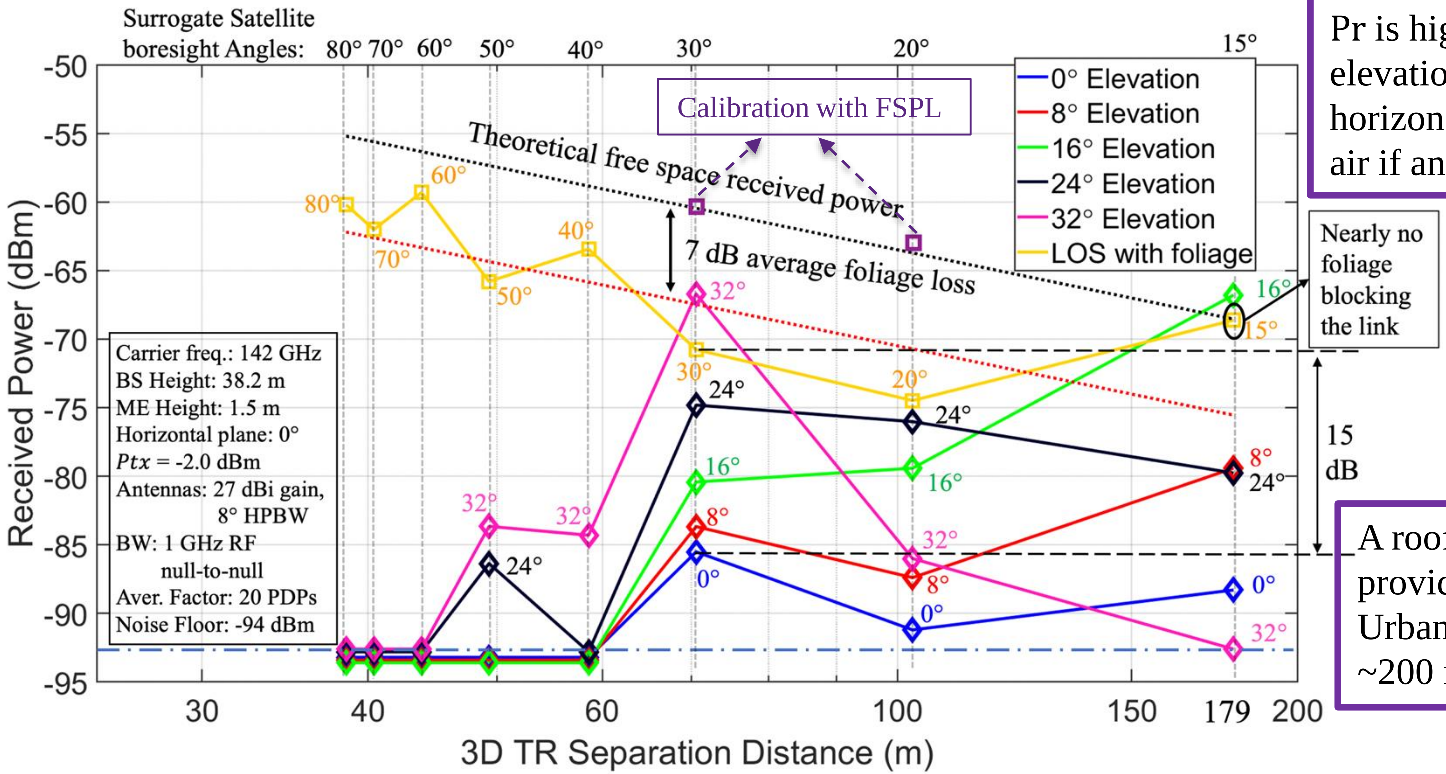
Measured Power Delay Profile of TX7-RXLoc1



When TX elevation is 0 ° (horizon), the transmitted signal to the rooftop RX is spatial filtered by the antenna pattern - No Signal at Roof

[1] Y. Xing and T. S. Rappaport, "Propagation Measurements and Path Loss models for sub-THz in Urban Microcells," in IEEE International Conference on Communications (ICC), Virtual/Montreal, pp.1-6, June 2021.

Surrogate Satellite Received Power vs. TX Locations and Elevation Angles



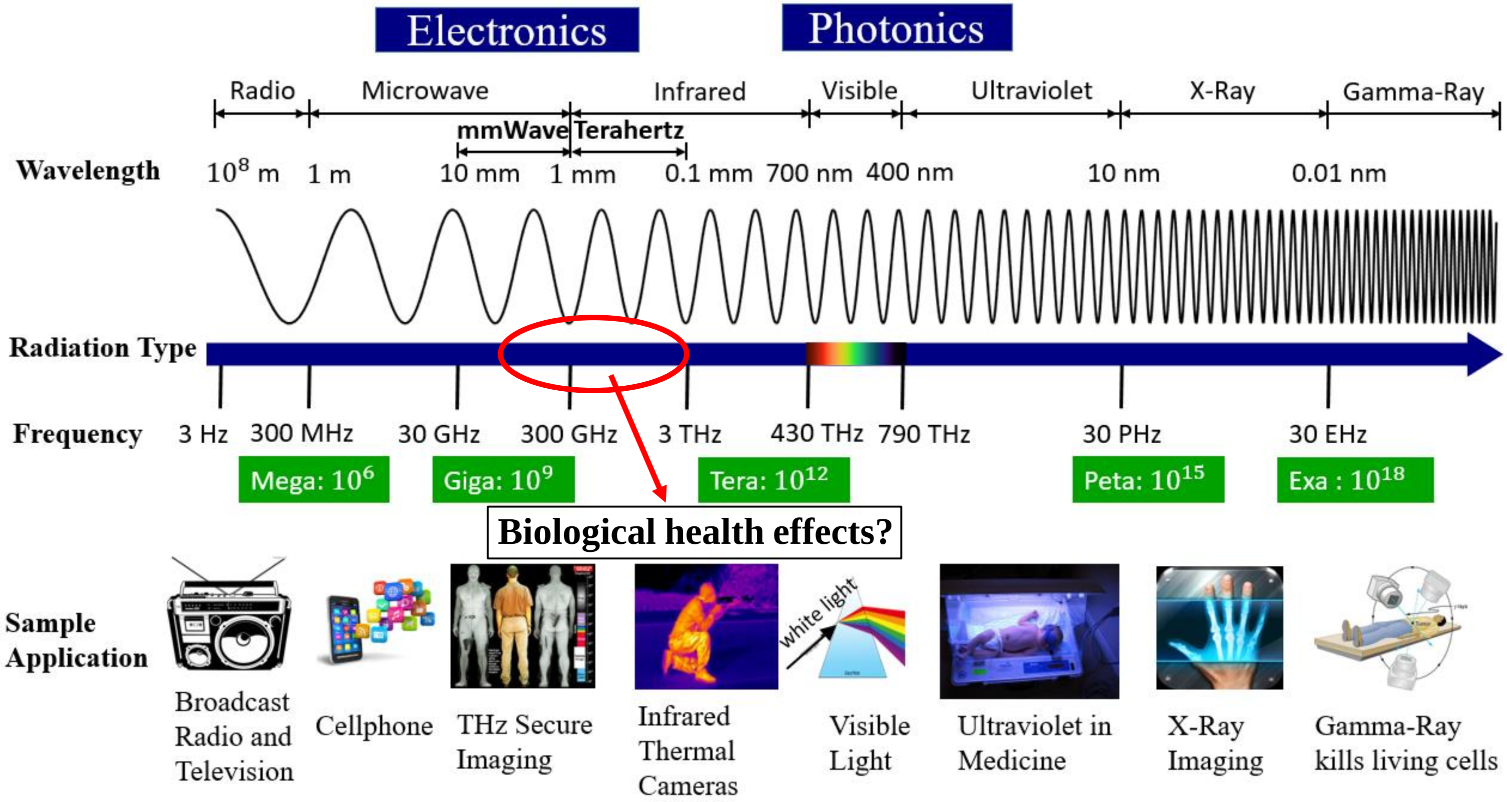
Pr is highly dependent on the elevation angles, propagation in the horizon will not cause interference to air if antennas are carefully designed

A rooftop base station can provide a good LOS coverage in Urban Microcell with a radius of ~200 m

Ptx = -2 dBm, 27 dBi gain 8° HPBW antennas at both TX and RX, average with 20 PDPs,
$Prx = Ptx + Gt + Gr - PL$, 500 MHz baseband bandwidth, sliding factor = 8000.

[1] Y. Xing and T. S. Rappaport, "Spectrum Coexistence between Active and Passive Systems in Space and on the Ground at Frequencies above 100 GHz (Invited)," in submission to IEEE Communication Letters, Feb. 2021, pp. 1-5.
[2] Y. Xing and T. S. Rappaport, "Propagation Measurements and Path Loss models for sub-THz in Urban Microcells," in IEEE International Conference on Communications (ICC), Virtual/Montreal, pp.1-6, June 2021.

Health Effects Above 100 GHz



[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)," in *IEEE Access*, vol. 7, pp. 78729-78757, 2019. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8732419

NYU Grossman School of Medicine

Current Consensus on RF Safety 6GHz-300GHz[1]

Heating at the very surface of the body is what matters

As frequency increases, so does potential for sensation of heating at a given power density

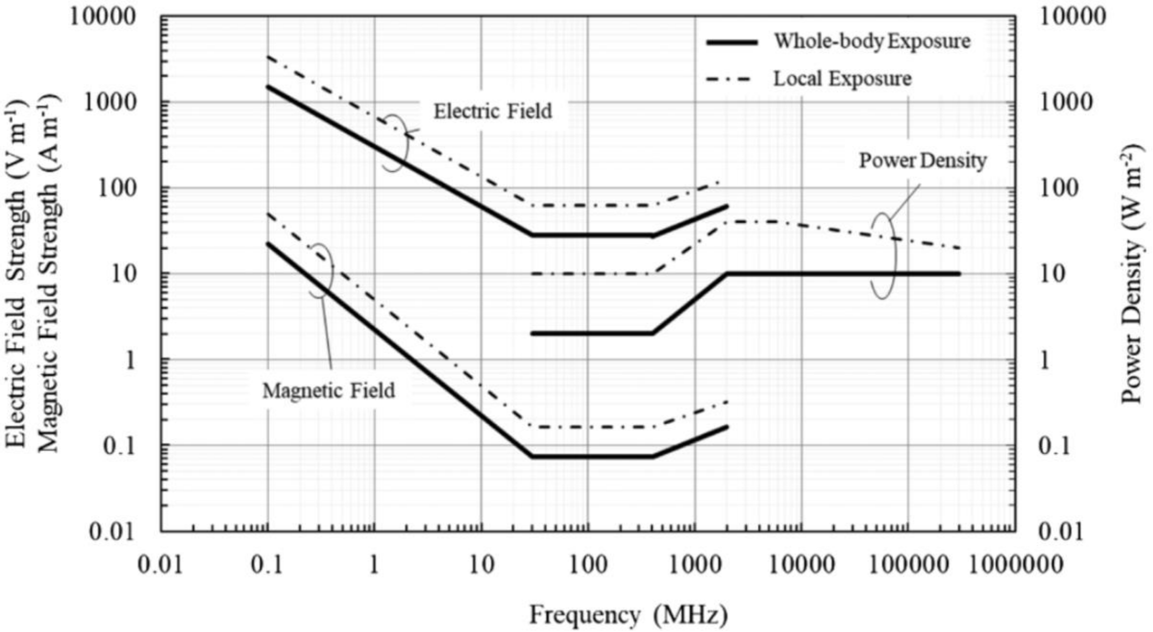
Cataracts are not likely to be induced below power densities that can burn skin

Power density limit of 10 W/m^2 likely conservative for 6GHz[2], but transmittance across skin is expected to increase with frequency[3]

Most recent guidelines (ICNIRP 2020[4]) try to take all this into account

1. IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz, 2019
2. Foster KR, Ziskin MC, Balzano Q. Health physics. 2017;113(1):41-53.
3. Sasaki K, Mizuno M, Wake K, Watanabe S. Physics in Medicine & Biology. 2017 Aug 9;62(17):6993
4. ICNIRP. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health physics. 2020 May 1;118(5):483-524.

NYU Grossman School of Medicine



Newly-published ICNIRP reference levels for time-averaged general public exposures of > 6 minutes, including both whole-body exposure (solid lines) and new local exposures (dash-dot-dash lines). At frequencies from 100 GHz (100,000 MHz) to 300 GHz (300,000 MHz), local power density exposures, defined as averaged over any 1cm^2, can exceed whole-body average exposures by a factor of 2.43 at 100Ghz to a factor of 2 at 300GHz.

ICNIRP. Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health physics. 2020 May 1;118(5):483-524.

NYU Grossman School of Medicine

RF Safety Capabilities at NYU Radiology Dept.

Simulations of multi-layer 1D representations of body surface and multi-dimensional representations also available

-Update and modification of past methods used

MRI-based Measurements of temperature increase in phantoms and human subjects

-Some development to get high-resolution surface imaging

Full suite of facilities for animal experiments and imaging

-With appropriate consensus and support regarding value of experiments

“Safe for Generations to Come”

Wu, Rappaport, Collins; IEEE Microwave Magazine, March 2015 pp. 56-84

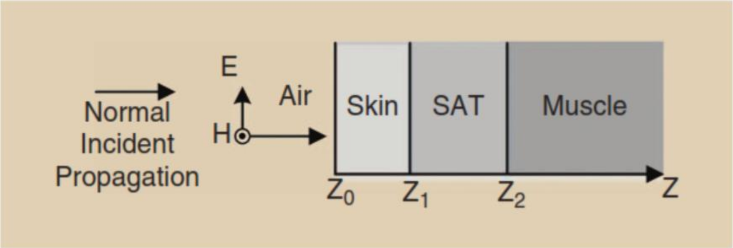


Figure 8. *A 1-D three-layer model of human tissue containing skin, SAT, and muscle.*

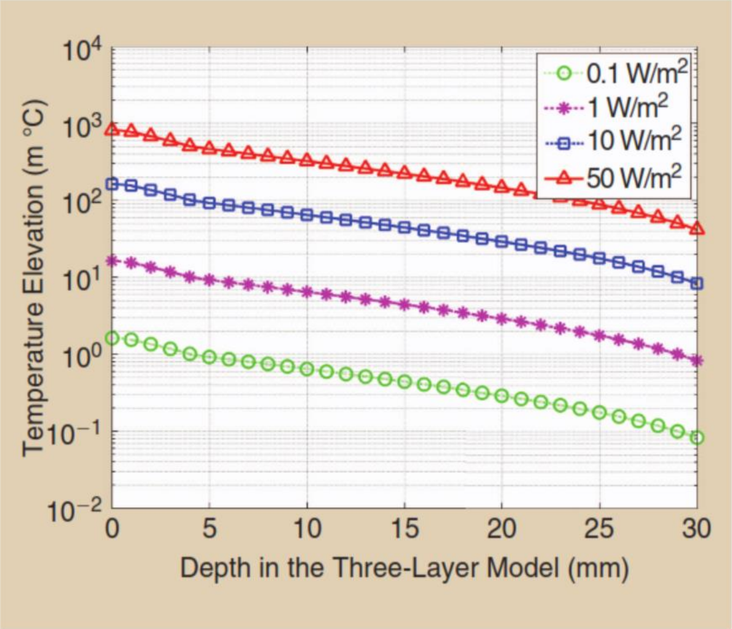
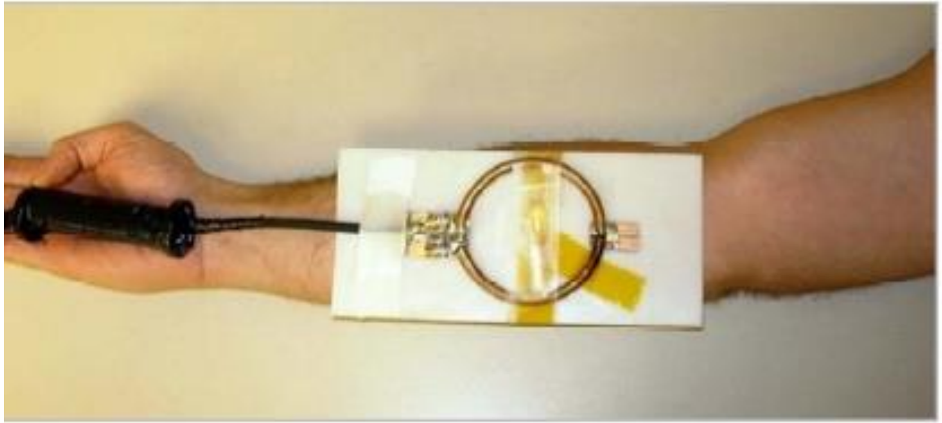


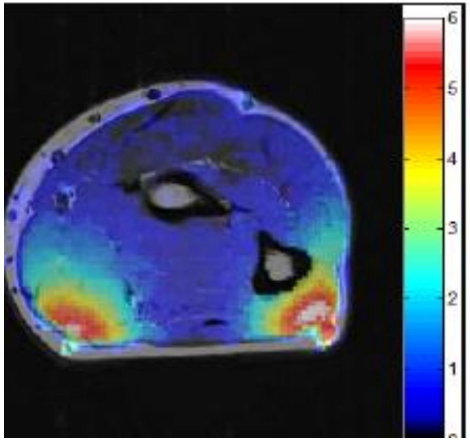
Figure 10. *The steady-state temperature elevation in the three-layer human tissue model at 60 GHz with different incident power densities.*

Using MRI to Measure Temperature Increase

<u>PRF shift thermometry:</u> change in MRI signal phase before and after heating translates to temperature change.

$$\Delta\phi(x,y,t) = \alpha\cdot\gamma\cdot B_0\cdot TE\cdot\Delta T(x,y,t)$$





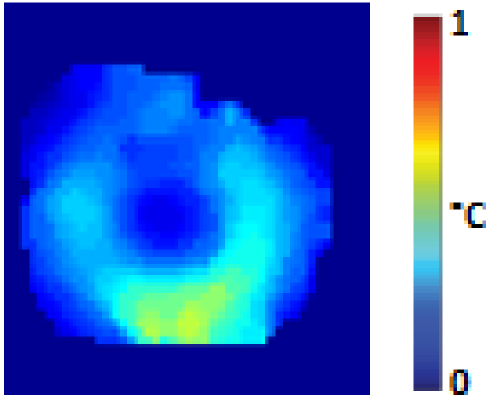
°C

Oh *et al.*, Magn Reson Med 2014;71:1923

- Fast
- High-resolution
- Noninvasive

MRI-based Thermal Mapping for Safety Assessment of Wireless Devices

→

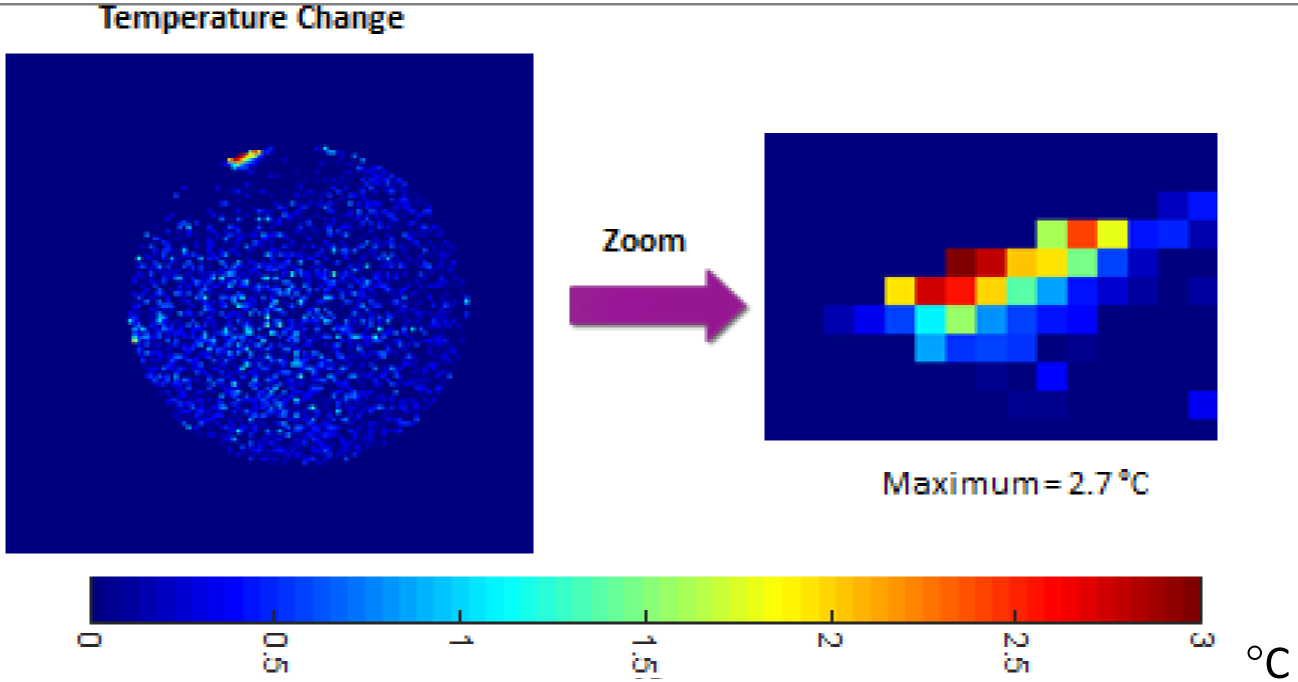


In collaboration with the Mobile Manufacturing Forum (MMF), we are conducting a compliance assessment pilot study of a prototype smart watch (Samsung).

3D thermal imaging will be conducted measuring the RF energy absorption from these device. An algorithm (next slide) will be used to convert to SAR

Courtesy of Leeor Alon, PhD: NYU Department of Radiology and RF Test Labs

Assessment of Heating at High Frequencies



24.245GHz

400 W/m²

5 min exposure in tissue-equivalent phantom

NYU Grossman School of Medicine

Animal Imaging & Monitoring Capabilities at NYU

- Methods for monitoring and analyzing differences in behavior and appetite with built-in cameras and scales

  Dr. Adam Mar

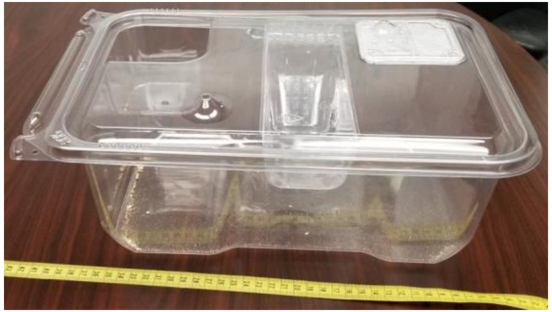
- 3 micro-MRI systems
- Micro CT/PET system
- 6 Bioluminescence and Flourescence optical scanners
- 4 high-frequency biomicroscopy ultrasound scanners

  Dr. Youssef Wadghiri

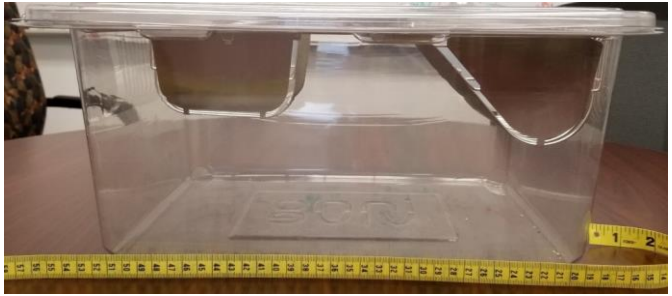
NYU Grossman School of Medicine

Standard Mouse and Rat "Cages" at NYU

Mouse



Rat



Results and Conclusions

- 5G has seen enormous progress since the "It Will Work!" paper in 2013
  - Global rollouts: engineers and technicians learning about mmWave directional channels
  - Governments are creating spectrum opportunities
  - FCC opened up frequencies above 95 GHz., others, too

- NYU WIRELESS needs to lead above 100 GHz
- 1 Early work shows **clear sailing channels** up to 800 GHz!
- 2. Interference Mitigation for mobile, fixed, earth, satellite (antennas, ICs, DSP)
  2a. Protection of astronomy and passive sensors critical – OOBE known/managed
- 3. Health Effects, heating primarily, but also non thermal need to be studied