Wireless Beyond 100 GHz: Opportunities and Challenges for 6G and Beyond

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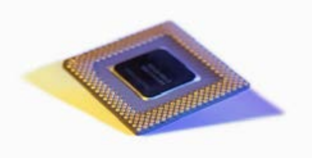
Outline

- 5G: How we got here and how we will move to 6G
- How 5G and small cells are evolving
- FCC Rulemaking/Regulatory Pressures and Needs
- Practical 5G and 6G Deployment issues
- 6G and Beyond! How it will happen

Research Goals (from 2010)

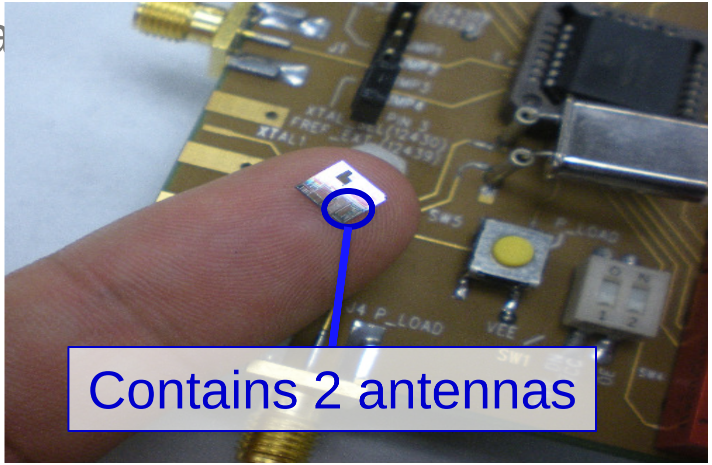
- Create integrated circuits (ICs) operating at millimeter-wave and terahertz frequencies (60 GHz and beyond)
- Using CMOS process – mainstream inexpensive fabrication technology that creates computer chips



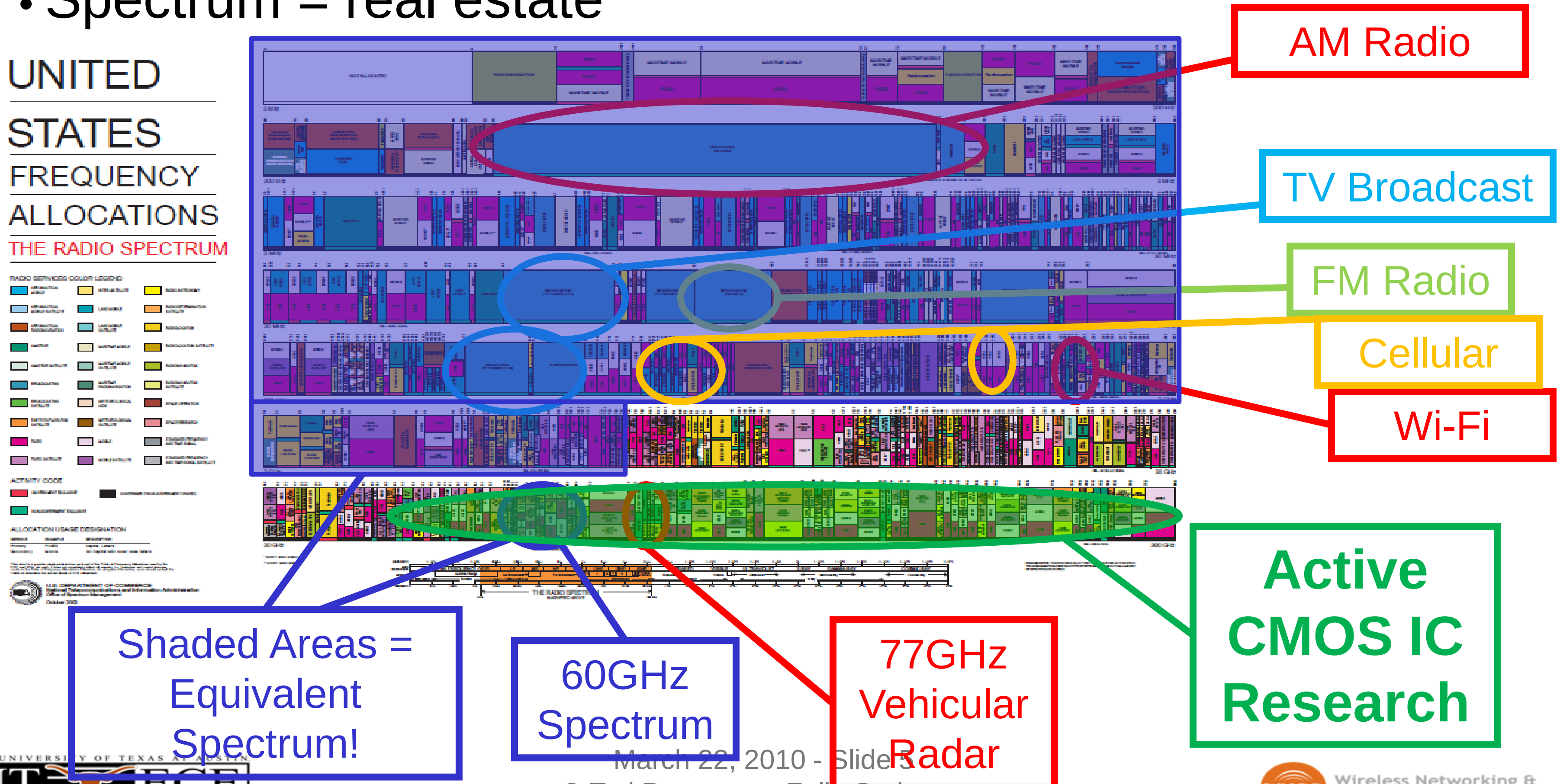
eras, and USB thumb drives

Why mmWave? (from 2010)

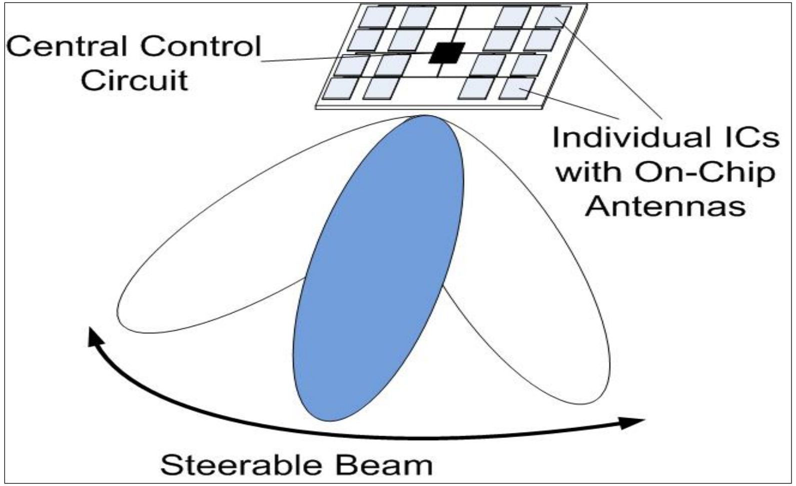
- **Huge** amounts of wireless spectrum available (currently unused)
- Able to send **massive** amounts of data (billions of bits every second) over local area (~10 meters)
- **Directionality** in sensing – vehicle radar
- Inexpensive CMOS fabrication now ca
- mmWave antenna sizes are comparable to integrated circuit (IC) sizes
- Tiny metal sheets available on ICs to fabricate mmWave/THz antennas
- **Reduces fabrication costs**
- **Low power, light weight, won't vibrate loose.**

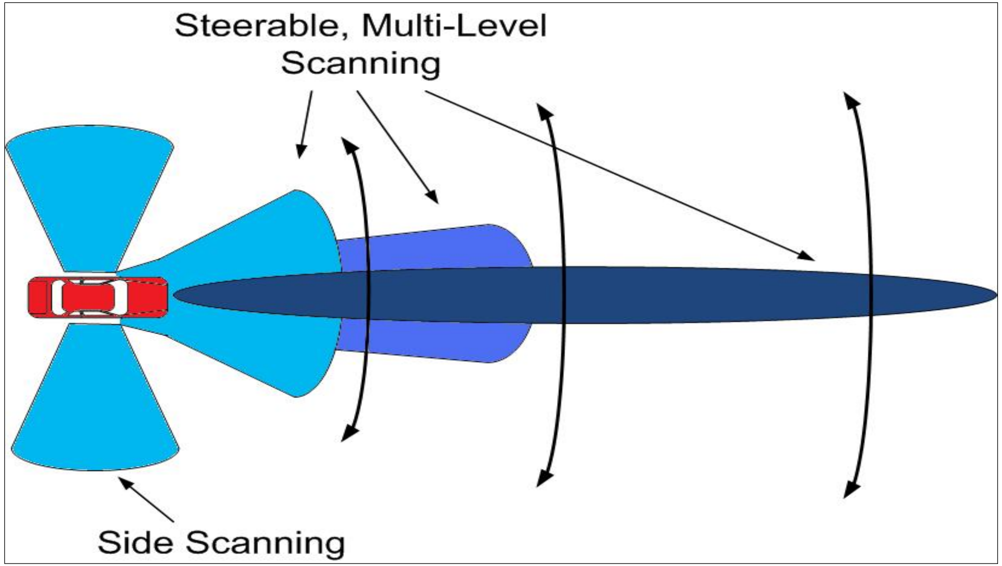


- Spectrum = real estate



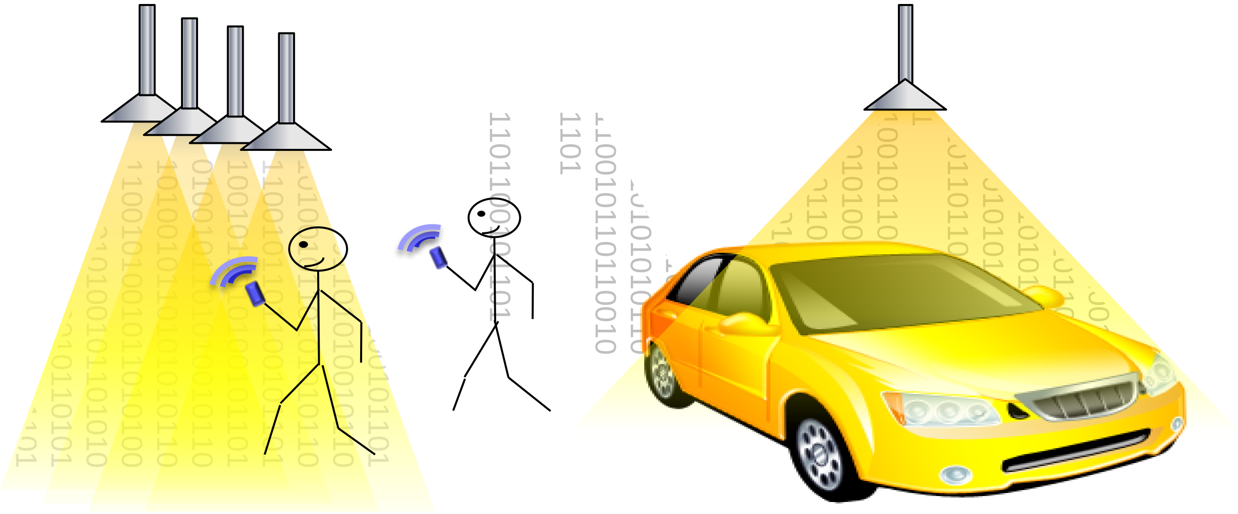
Applications - Vehicle Radar





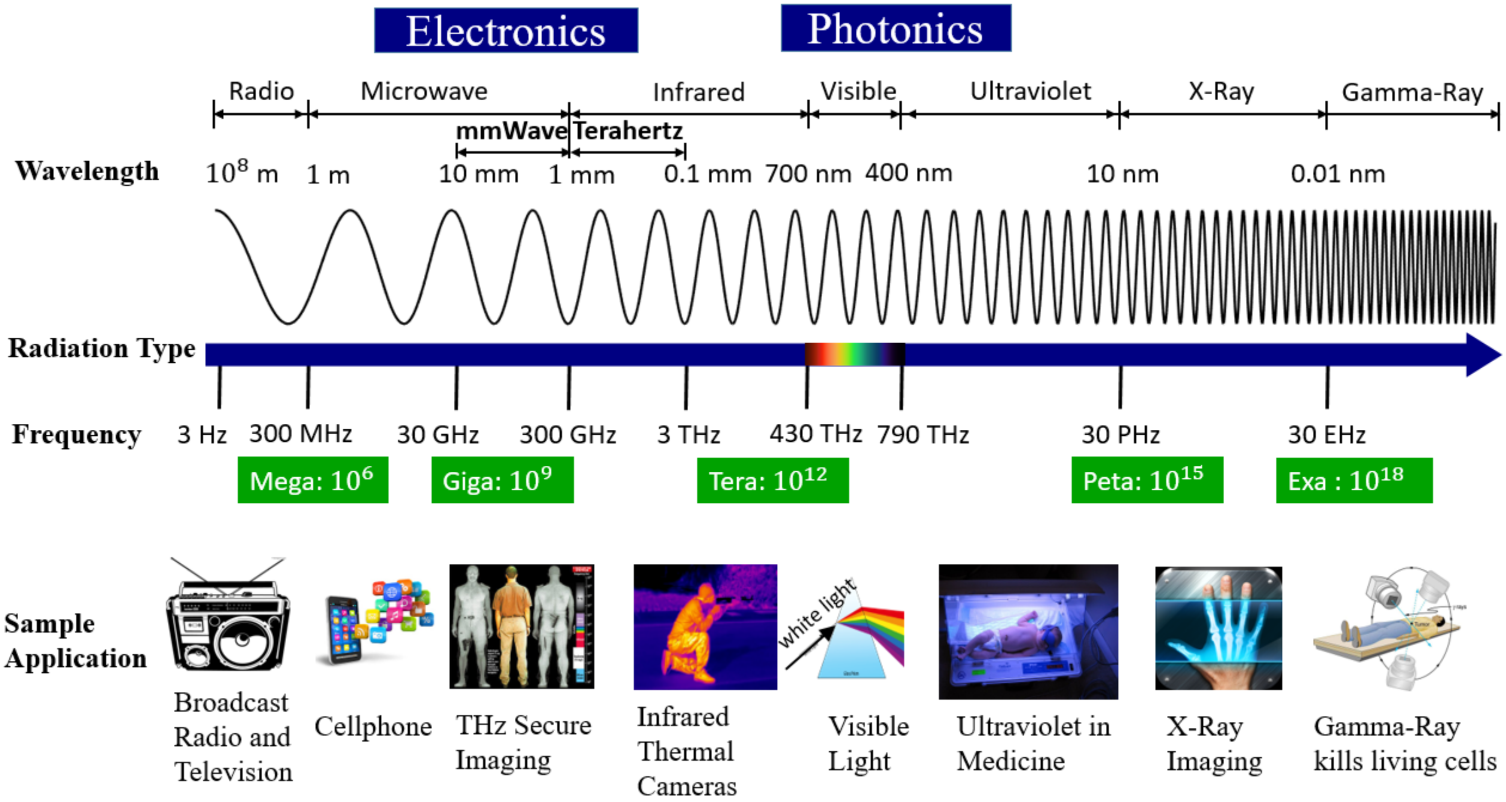
- Phased array of IC antennas
  - Directional beam for long distance vehicle radar and collision avoidance
  - Steerable beams

Information Showers



- The future: Showering of information
- Mounted on ceilings, walls, doorways, roadside
- Massive data streaming while walking or driving
- Roadside markers can provide safety

The Radio Spectrum



[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

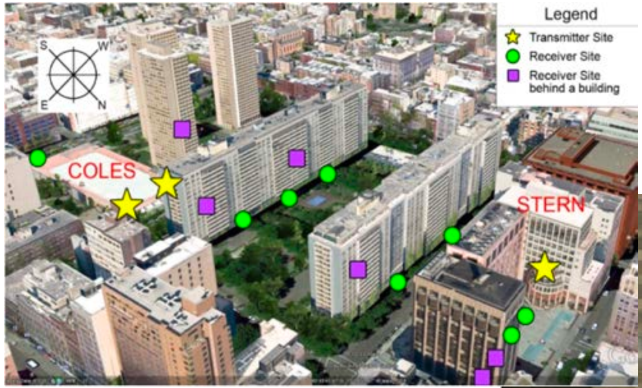
5G Motivation & mmWave Measurements

- **Spectrum shortage** in microwave band motivates use of **millimeter wave (mmWave)** for 5G cellular
- **Channel measurements** and **channel model** needed for mmWave communications

Pioneering mmWave propagation measurements in New York City by NYU WIRELESS

28 GHz & 73 GHz urban microcell (UMi), urban macrocell (UMa), small-scale fading, indoor office measurements, and 73 GHz rural macrocell (RMa) measurements from 2012 to 2017

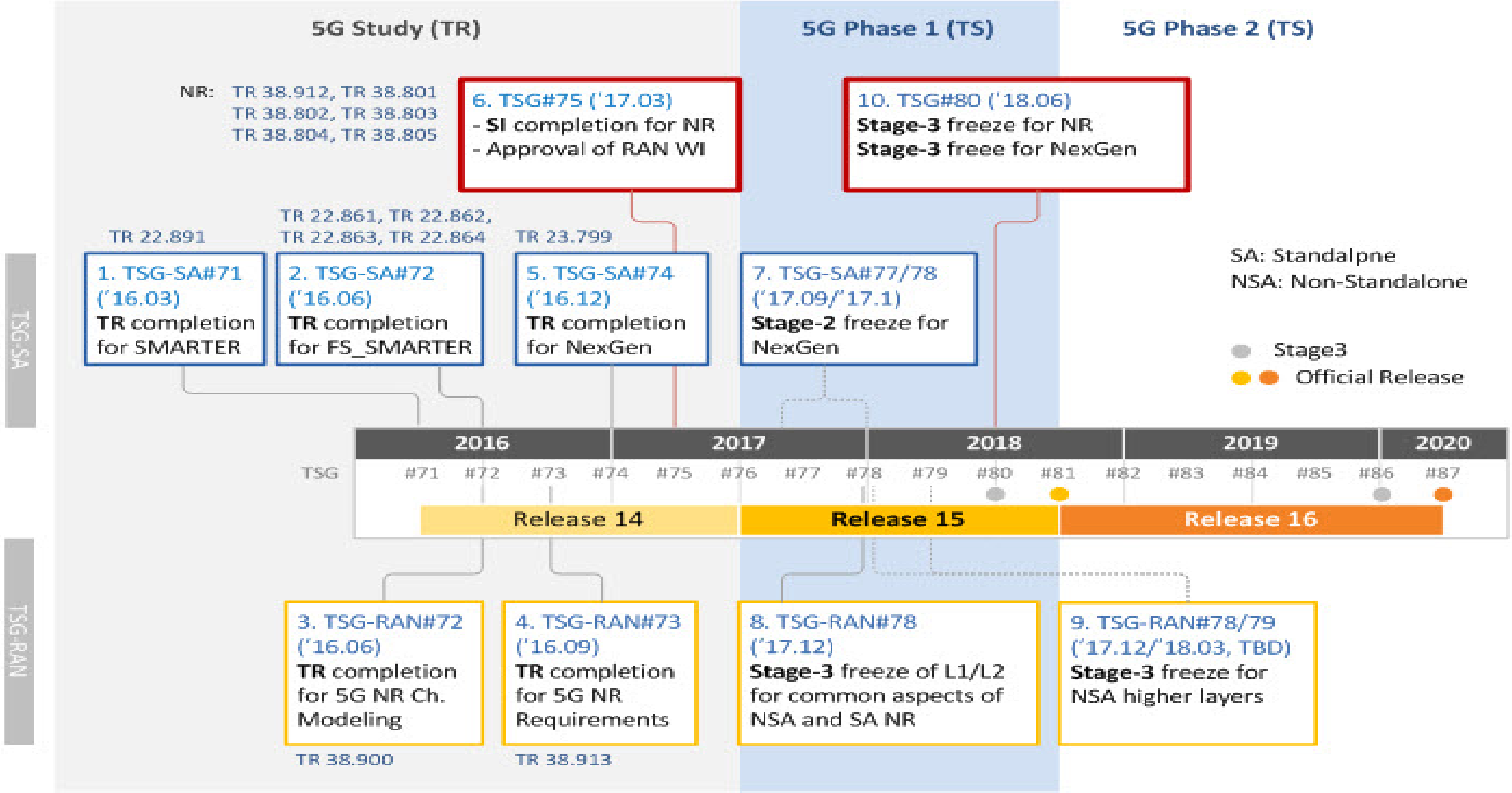
Carrier Freq.	28 GHz
RF Bandwidth	800 MHz
TX & RX Antenna Type	Rotatable Horn Antenna
TX & RX Ant. Gain	24.5 dBi; 15 dBi
TX & RX AZ Ant. HPBW	10.9^0; 28.8^0
TX & RX EL Ant. HPBW	8.6^0; 30^0
TX & RX Ant. Sweep	Yes
TX Height	7 m, 17 m
RX Height	1.5 m
Max. TX Power	30.1 dBm
Max. Measurable Path Loss	178 dB



28 GHz UMi & UMa measurements in 2012

T. S. Rappaport *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE Access*, vol. 1, pp. 335-349, 2013.
T. S. Rappaport *et al.*, "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design," *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029-3056, Sep. 2015.

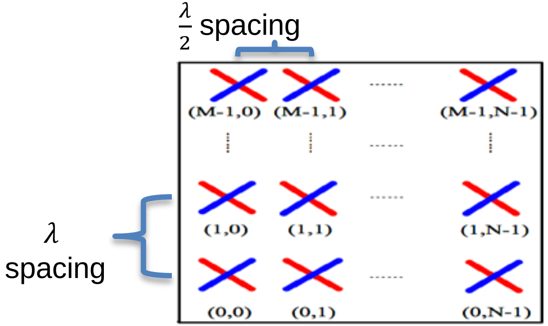
5G Standard timeline



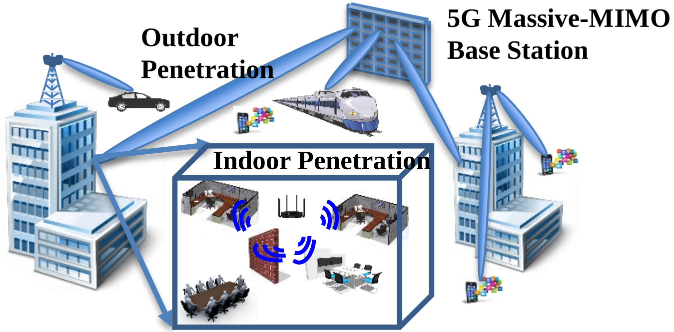
https://www.netmanias.com/en/post/oneshot/11147/5g/timeline-of-5g-standardization-in-itu-r-and-3gpp

5G in a Nutshell

- Pre-5G: Cellphone systems operated at 1 -2 GHz (microwave)
- 5G uses 1-2 GHz (low), 2.6 GHz (mid) **and** mmW (high band) high band is 24, 28, 37, 39 GHz spectrum
- 5G mmW Channel Bandwidths are 20X 4G →50X 4G speed!
- 5G Latency is less than 10 milliseconds (imperceptible)
- 5G: 10 Gigabit per second transmissions to a phone (like fiber!)
- 5G exploits smaller wavelengths → permits more antennas in each cellphone and base station – steerable beams!
- **Cross Polarization Discrimination** (XPD) and **small cells** overcome penetration loss, human blockage, foliage loss in 5G



(a) Dual-polarized antenna array [2]



(b) Penetration in 5G mmWave communications

[1] T. S. Rappaport, et. al., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEEE Access Vol. 1, no. 1 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6515173

[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. https://arxiv.org/pdf/1803.03986.pdf ; See also https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8386686

A Simple Comparison Between LTE and 5G New Radio (NR)

	LTE	5G NR (eMBB)
Number of Streams	SISO	SISO
BW	20 MHz	800 MHz
Subcarrier spacing	15KHz	240KHz
FFT size	2048	2048
Number of Occupied Subcarrier	1200	~1600
Spectral Occupancy	90%	98%
Slot Duration	0.5 ms [7symbols]	65us [14 symbols]
Antenna	Omni	64 Beams

NATIONAL INSTRUMENTS™

4G and 5G BS Antenna Comparison

4G LTE Advanced Pro [1,2]:

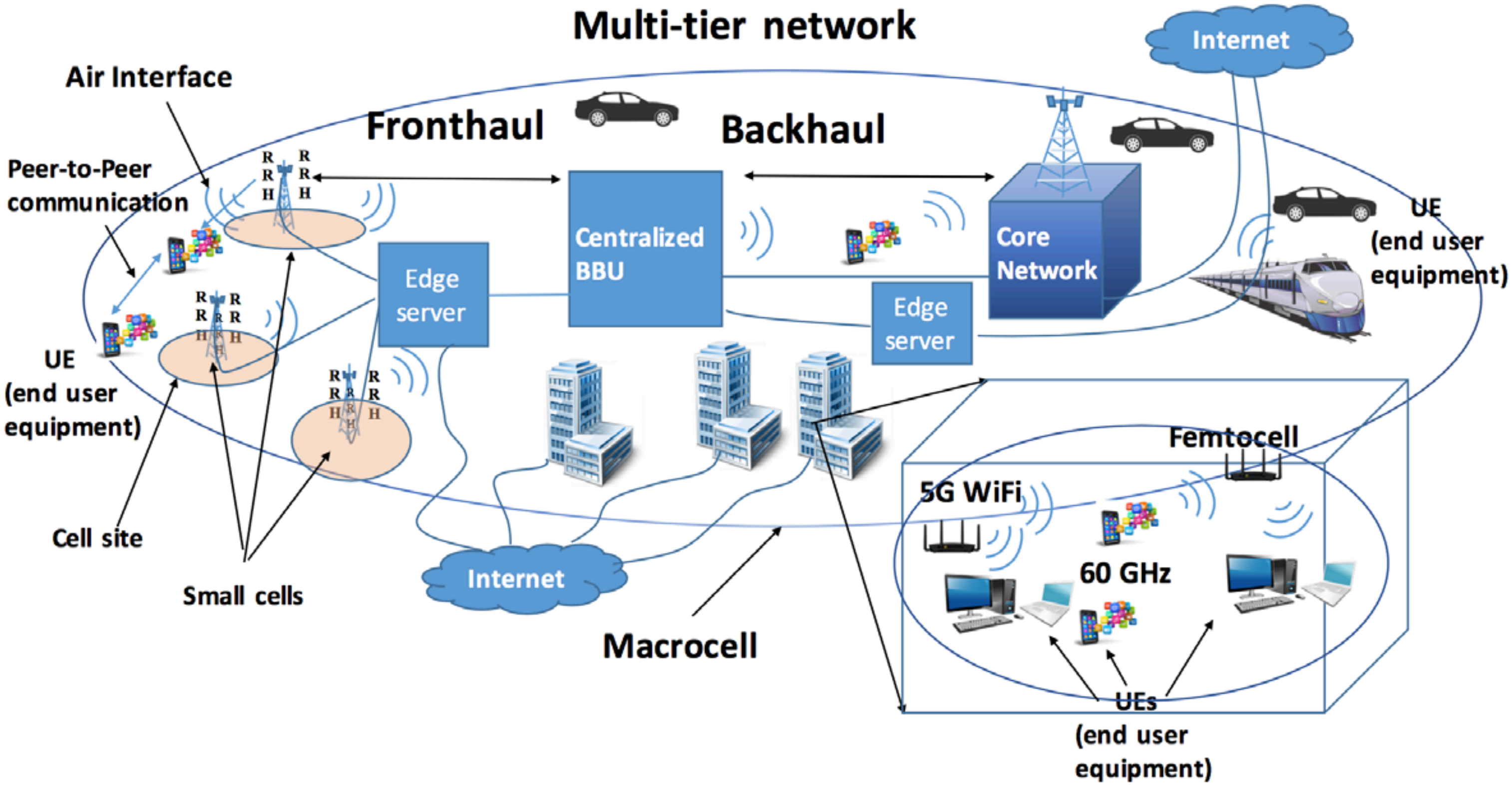
- ≤ 64 antenna elements
- 1-2 Gbps data rate
- ~10 ms latency
- Digital beamforming

5G NR [3, 4]:

- ≥ 256 antenna elements (but same size)
- BS Placement: site-specific sensitivity
- > 10 Gbps data rate
- < 1 ms latency
- Hybrid beamforming [4] (most possible)

[1] 3GPP TR36.897 V13.0.0: "Study on elevation beamforming / full-dimension (FD) multiple input multiple output (MIMO) for LTE," Jun. 2015.
[2] 3GPP TR 36.819 V11.2.0, "Coordinated multi-point operation for LTE physical layer aspects," Sep. 2013.
[3] 3GPP TR 38.802 V14.2.0: "Study on new radio access technology – physical layer aspects," Sep. 2017.
[4] 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.

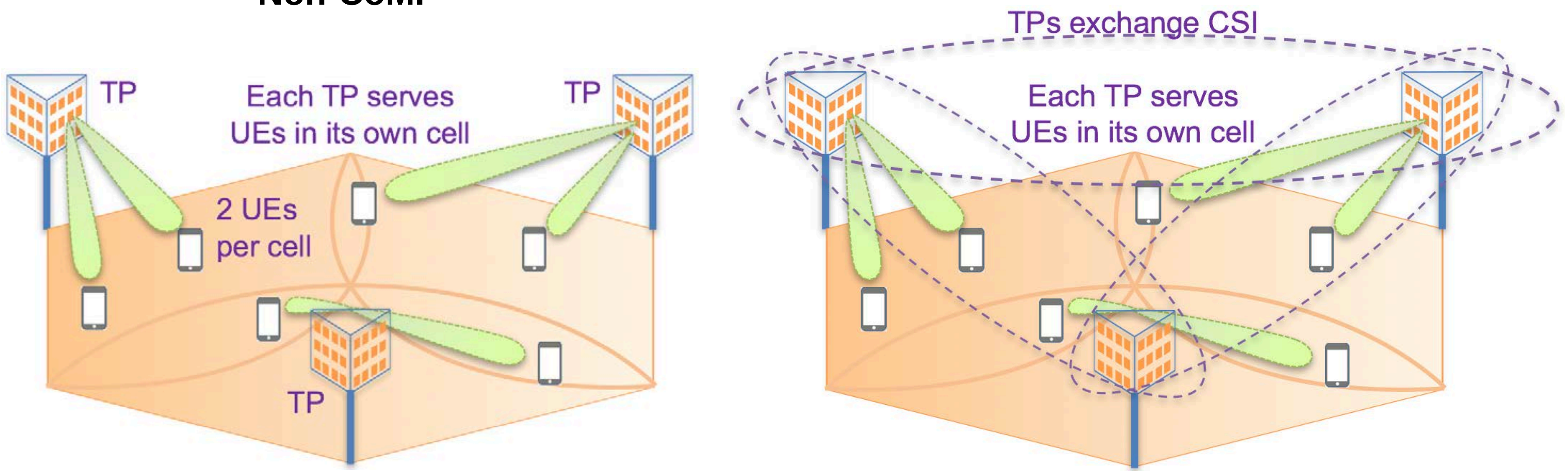
5G Multi-tier network [1]



[1] 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," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213-6230, Dec. 2017. https://ieeexplore.ieee.org/document/7999294

Example illustrations showing the difference between non-CoMP and CoMP（coordinated scheduling/beamforming from Transmission Points TP）

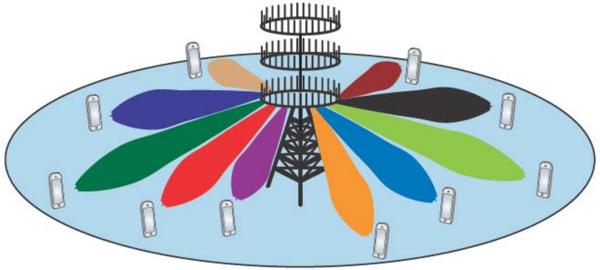
Non-CoMP | **CoMP**（coordinated scheduling/beamforming）[1]



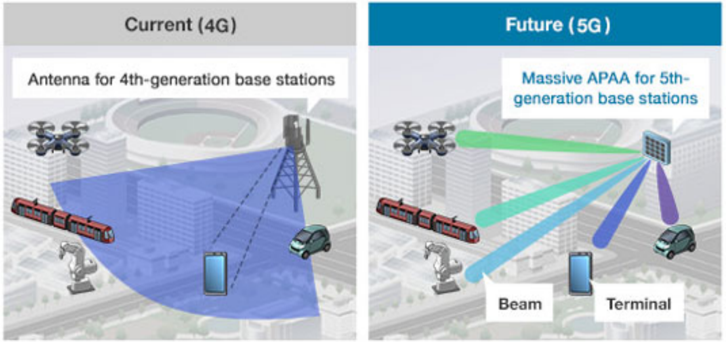
[1] 3GPP, "Coordinated multi-point operation for LTE physical layer aspects," 3rd Generation Partnership Project (3GPP), TR 36.819 V11.2.0, Sep. 2013.

5G Base Stations and Network Architecture [1]

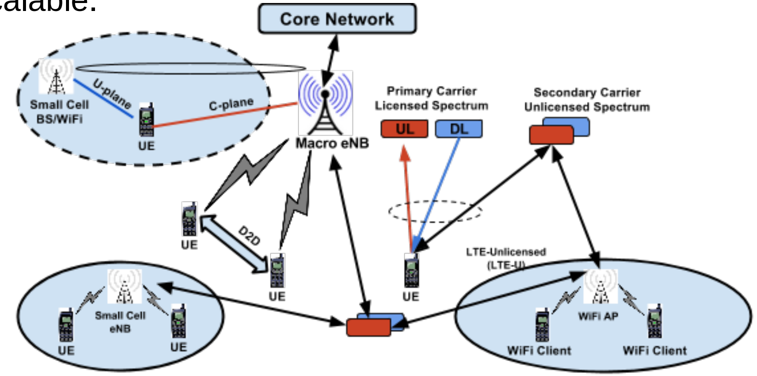
5G base stations (Nokia 5G AirScale Base Station [2]).



5G Massive MIMO, here ten user terminals and one hundred BS antennas. The antenna array is scalable.



The directionality of 5G base stations.



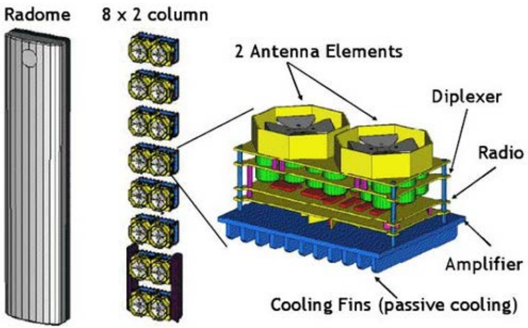
Heterogeneous 5G networks, Small cells and WiFi [3]

[1] 3GPP TR 38.802 V14.2.0: “Study on new radio access technology – physical layer aspects,” Sep. 2017.
[2] https://networks.nokia.com/products/airscale-base-station
[3] http://www.openairinterface.org/?page_id=458

4G LTE Base Stations and Antennas [1,2]

Cellular antennas on a lattice tower: low/mid band (Katherin)

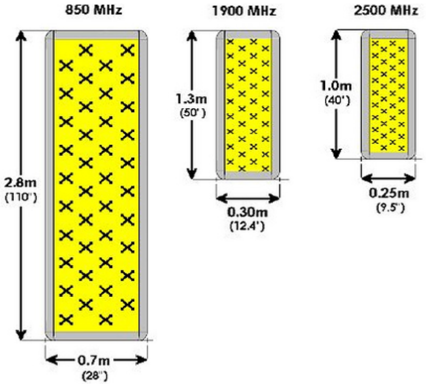
Bass drum in the sky, courtesy of CommScope [3].



A example of 8×2 antenna array architecture [4].

Streetlight small cells (CommScope).

Cell sites on rooftops.



Typical and Relative Multi-column Antenna Size for [4]:

- 850 MHz, 1900 MHz, 2500 MHz (2.6 GHz)
- 4-column planar arrays with 0.5 wavelength spacing

[1] 3GPP TR36.897 V13.0.0: "Study on elevation beamforming / full-dimension (FD) multiple input multiple output (MIMO) for LTE," Jun. 2015.
[2] 3GPP TR36.884 V13.1.0: "Performance requirements of MMSE-IRC receiver for LTE BS," Sep. 2016.
[3] https://hackaday.com/2016/04/05/a-field-guide-to-the-north-american-communications-tower/
[4] http://www.dailywireless.org/2010/05/13/mimo-the-paper-war/

5G mmWave and Massive Mimo Antennas [1,2]

Sprint Massive MIMO at 2.6 GHz in New York City [1]

Sprint Massive MIMO and In-band backhaul @2.6 GHz

5G Base Station at 28 GHz on top of 4G LTE in Chicago on the Verizon Network [2].

5G RF front end and antenna on light pole

[1] https://www.reddit.com/r/Sprint/comments/94bfwd/sprint_massive_mimo_live_in_nyc/ Reddit 2018 Sprint in NYC
[2] https://www.pcmag.com/news/367659/heres-the-real-truth-about-verizons-5g-network PC Magazine 2019 Verizon Chicago

5G FCC Regulation Challenges

- **Small cells, zoning efforts**
- **How to manage radiated power with beamforming antennas**
- **Political/technical debate at 24 GHz- Weather Forecasting at 24 GHz**
- **Freeing up mid-band spectrum (3.2 – 4.7 GHz) for wireless industry**
- **There are many more- these are just some examples**

Small Cells, Zoning Efforts

- **Declaratory Ruling: Small Cells WT Docket 17-79, WC Docket 17-84 [1]**
- **Broad industry standards better than individual local govt. ordinances**
- **Examples of individual cities/municipalities, 9 cu. ft. footprint:**
- San Mateo, CA:
- https://www.cityofsanmateo.org/DocumentCenter/View/64833/Final-Design-and-Engineering-Standards?bidId
- Council Bluffs, IA:
- https://www.councilbluffs-ia.gov/DocumentCenter/View/6260/Small_Cell_Policy_Guidelines
- Charleston, SC:
- https://www.charleston-sc.gov/DocumentCenter/View/20423/Requirements-for-Small-Cell-Wireless-FacilitiesPermitting-and-Placement-in-Rights-of-Way?bidId=
- Syracuse, NY:
http://www.syrgov.net/uploadedFiles/Departments/Engineering/Content/Syracuse%20Small%20Wireless%20Facilities%20Design%20Standards%20-%20April%202019.pdf
- San Francisco, CA (Steel poles):
http://default.sfplanning.org/currentplanning/wireless/FAQ_Small_Cells_on_Steel_Light_and_Transit_Poles.pdf
- San Francisco, CA (Wooden poles):
http://default.sfplanning.org/currentplanning/wireless/FAQ_Wireless_Facilities_on_Poles.pdf

[1] https://docs.fcc.gov/public/attachments/DOC-353962A1.pdf FCC Fact Sheet Sept. 5, 2018

How to Manage Radiated Power

- **Multiple antenna elements and beamforming are new**

- **Part 30 currently states:**

  §30.202 Power limits.

  (a) For fixed and base stations operating in connection with mobile systems, the average power of the sum of all antenna elements is limited to an equivalent isotopically radiated power (EIRP) density of +75dBm/100 MHz. For channel bandwidths less than 100 megahertz the EIRP must be reduced proportionally and linearly based on the bandwidth relative to 100 megahertz.

  (b) For mobile stations, the average power of the sum of all antenna elements is limited to a maximum EIRP of +43 dBm.

  (c) For transportable stations, as defined in §30.2, the average power of the sum of all antenna elements is limited to a maximum EIRP of +55 dBm.

  (d) For fixed point-to-point and point-to-multipoint limits see §30.405.

[1] https://docs.fcc.gov/public/attachments/DOC-353962A1.pdf FCC Fact Sheet Sept. 5, 2018

NOAA v FCC Debate at 24 GHz

- **Passive Satellites measure the noise temperature of water molecules**
- **Measure passively at 22.8 GHz and surrounding bands to 30 GHz**
- **The weather models are incredibly noisy!**
- **No wonder weather radar prediction is so poor (See figs 1-3!)**
- **http://radiometrics.com/data/uploads/2012/11/liljegren_TGRS04.pdf**

- **415 MHz separation from 23.835 GHz (WX) and 24.250 GHz (5G)**
- **Up for debate, but easy to calibrate out any out of band – if an issue!**
- **Systematic study could easily be done. I think § 30.202 has it right**
- **-20 dBW per 200 MHz out of the passband (10 mW over 200 MHz!)**
- **FCC View:**
- **https://www.multichannel.com/news/fcc-pai-study-on-24-ghz-weather-data-issue-is-fundamentally-flawed**
- **NOAA/NIST View:**
- **https://physicsworld.com/a/debate-rages-over-5g-impact-on-us-weather-forecasting/**

http://radiometrics.com/data/uploads/2012/11/liljegren_TGRS04.pdf

Political Technical Debate at 24 GHz

- **Myriad of Satellites are used (mmWave use Low Earth Orbit ~ 500 mi)**
- **https://severe.worldweather.wmo.int/TCFW/RAIV_Workshop2016/06_Satellites_JackBeven.pdf**
- **23.835 GHz is just a single frequency from myriad inputs**

- **Types of Satellite Data**

• Tropical Cyclone Intensity Estimates (VIS, IR, MW)
NOAA (Advanced Microwave sounding Unit or AMSU)
DMSP (SSM/IS), GPM, GCOM, METOP, NPP (ATMS)
*** Satellite Vertical Soundings (IR, WV/EHF, MW)**
- GOES, NOAA, DMSP, METOP, Aqua, NPP
*** Ocean Wave Heights (Jason2, Jason 3, Cryosat, Altika)**
*** Oceanic Heat Content (Jason2, Jason 3, Cryosat, Altika)**

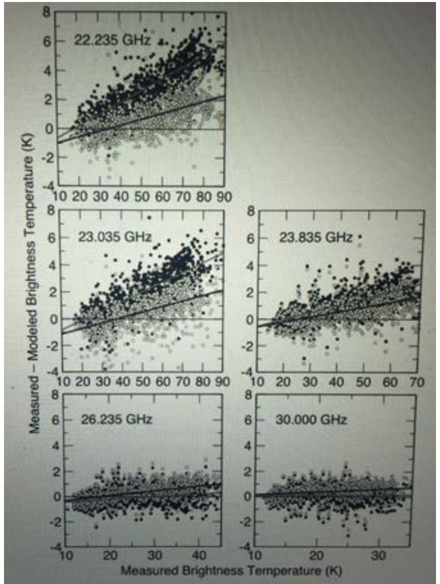


Fig.1. Differences between measured and model-calculated brightness temperatures for the half-width of the 22-GHz absorption line from Liebe and Dillon [10] (solid circles, gray regression line) and the half-width from HITRAN [11] (open circles, black regression line) for liquid-water-cloud-free conditions.

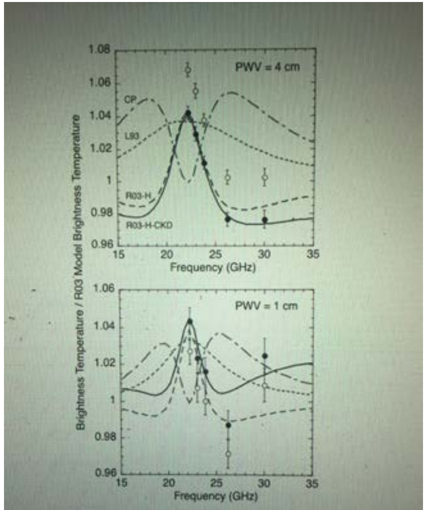
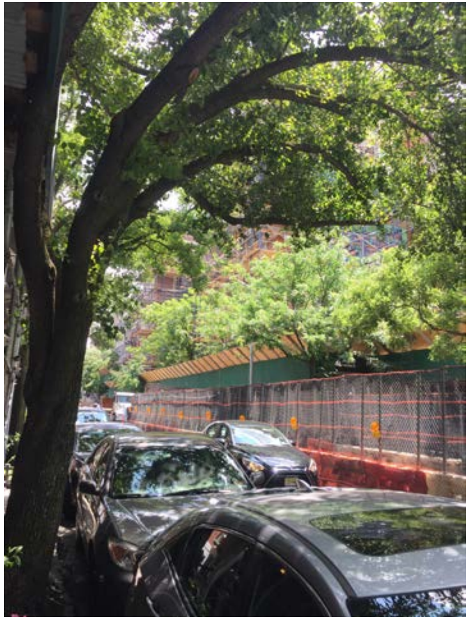


Fig. 3. Ratios of brightness temperature from modified versions of the Rosenkranz absorption model to results from the original model (R03) for 4 cm PWV (top) and 1 cm PWV (bottom): HITRAN half-width at 22 GHz (R03-H), HITRAN half-width and water vapor continuum adjustments consistent with MT_CKD [15] (R03-H-CKD), 5% increase in 22-GHz line strength per Liebe *et al.* [13] (L93) and 6.4% increase in strength plus 6.6% increase in width per Cruz Pol *et al.* [14] (CP). Open circles are the mean ratio for measured T_B between 0.75 and 1.25 cm PWV and between 3.75 and 4.25 cm PWV; error bars are 99% confidence limits. Solid circles are the same as the open circles but are adjusted to agree with R03-H-CKD at 23.835 GHz.

http://radiometrics.com/data/uploads/2012/11/liljegren_TGRS04.pdf
https://severe.worldweather.wmo.int/TCFW/RAIV_Workshop2016/06_Satellites_JackBeven.pdf

Practical Implementation of 5G

- 5G mmW Propagation within Cities (consider New York City):
- Local Law 10, 11 – all building facades must be inspected 4-5 years
- 25% of all buildings in Manhattan will always have scaffolding in front!
- Estimate a 2X increase in small cell base sites due to this effect!

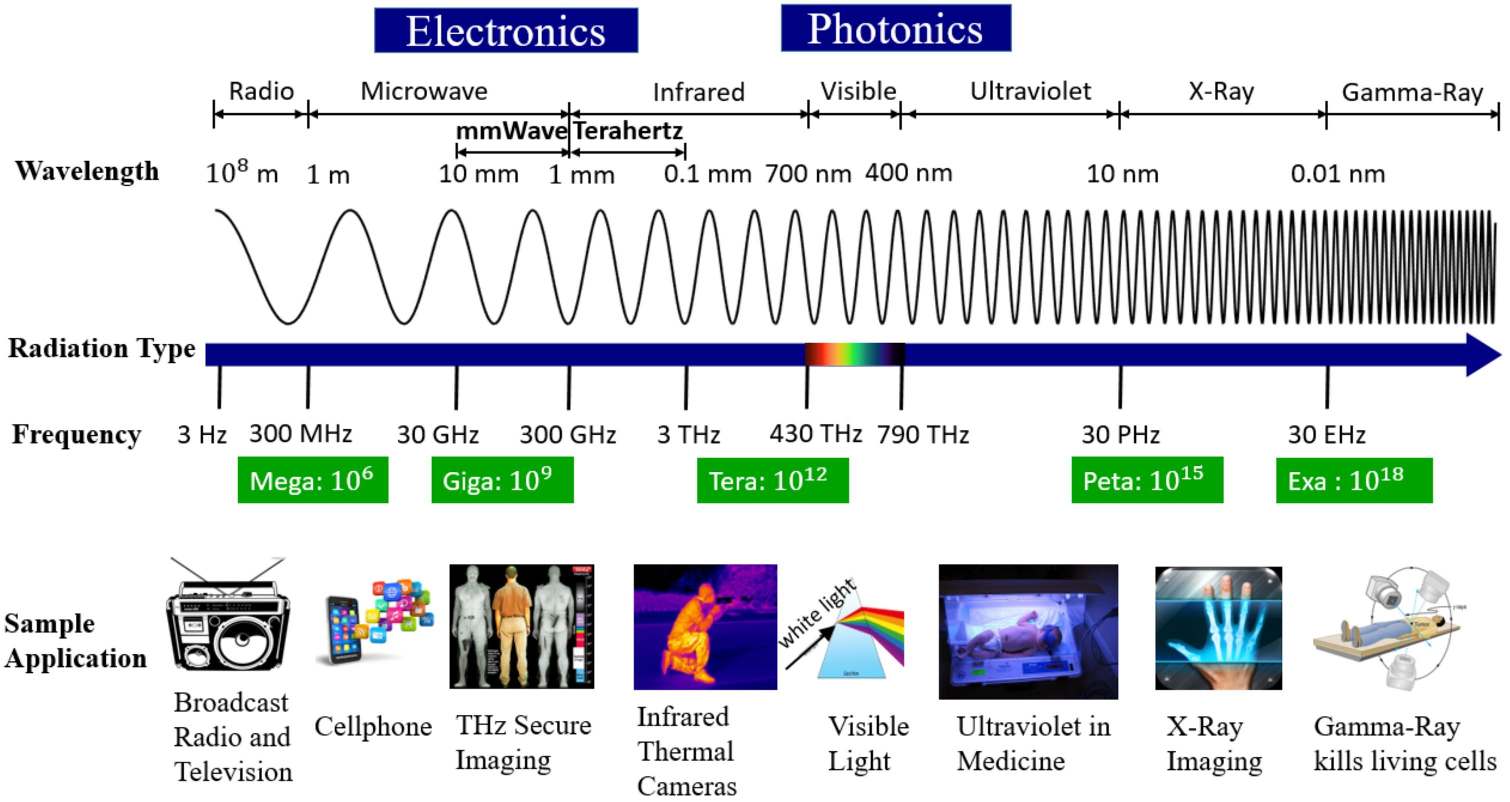


Practical Implementation of 5G

- **The 5G Health Hazard that isn't (NYT: William Broad, July 16, 2019)**

  - **https://www.nytimes.com/2019/07/16/science/5g-cellphones-wireless-cancer.html**
  - **Radio Waves do not travel deeply into people as frequencies go up to mmW and above**
  - **People are more reflective than they are absorbing – RF heating is the key issue to avoid**
  - **NYU did key work on this in 2015: "Safe for Generations to Come","Human Body Interactions"**
  - **FCC needs to make safety regulations for above 95 GHz (JA, RUS, EU goes to 300 GHz)**
  - **Coherent energy from multi-element antennas should be considered into the future**
  - **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4629874/**
  - **https://arxiv.org/ftp/arxiv/papers/1503/1503.05944.pdf**

Moving to 6G 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)," IEEE ACCESS, Vol. 7, No. 7, June 2019 https://ieeexplore.ieee.org/document/8732419

The THz Band

NYU TANDON SCHOOL OF ENGINEERING

NYU WIRELESS

1933

FM Radio
(~100 MHz)

1973

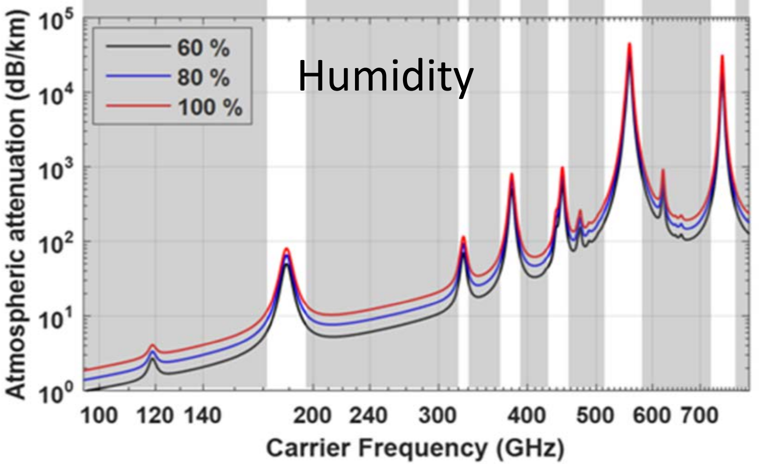
First handheld phone
(~850 MHz)

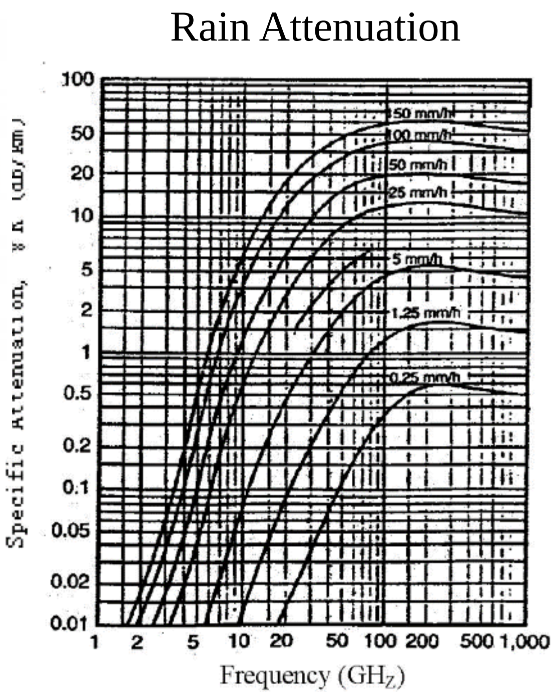
20

WIFI (~2.4 and 5 GHz)

2019

Foldable Smart Phone (~3.5 GHz)





100 Years - 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.

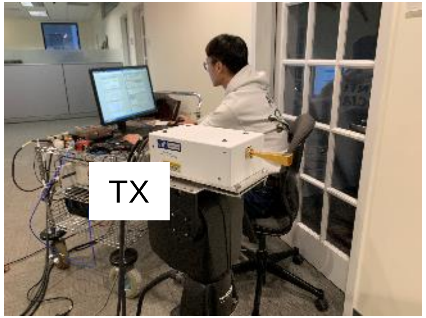
[3] Q. Zhao and J. Li, ''Rain attenuation in millimeter wave ranges,'' in Proc. IEEE Int. Symp. Antennas, Propag. EM Theory, Oct. 2006, pp. 1–4.

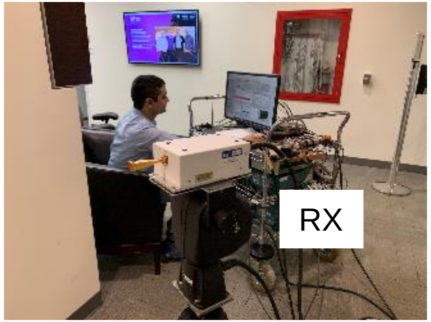
[4] mmWave Coalition's NTIA Comments, Filed Jan. 2019. http://mmwavecoalition.org/mmwave-coalition-millimeter-waves/mmwave-coalitions-ntia-comments/

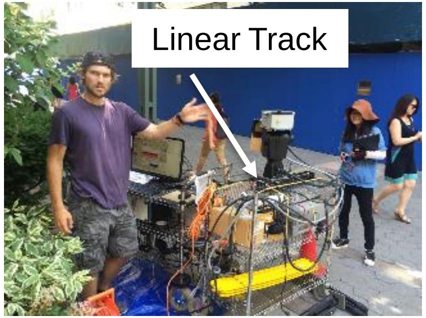
[29] J. Ma et. al., "Channel performance for indoor and outdoor terahertz wireless links," APL Photonics, vol. 3, no. 5, pp. 1–13, Feb. 2018.

140 GHz Channel Sounder

Conducting indoor/ outdoor measurements [21]







140 GHz broadband channel sounder [22]

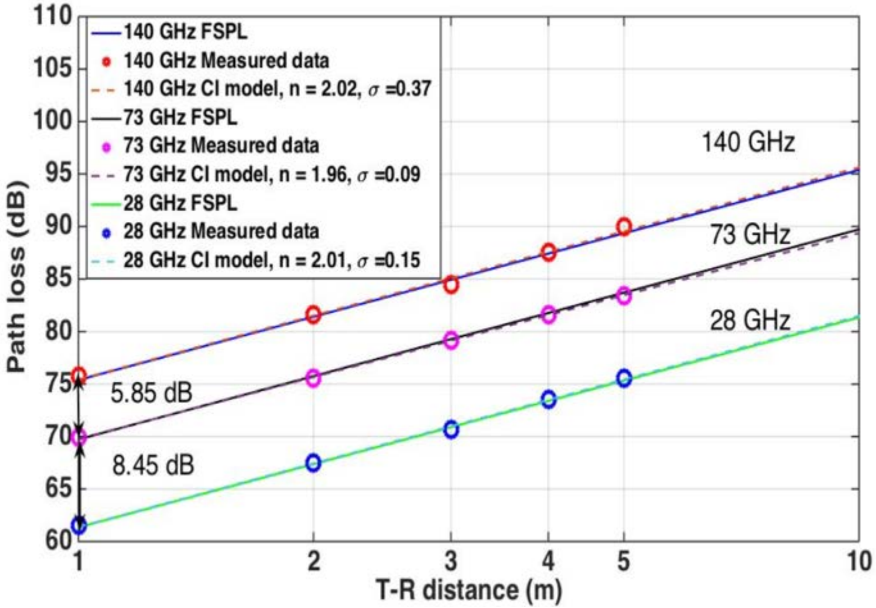
[21] Y. Xing and T. S. Rappaport, “Propagation Measurement System and approach at 140 GHz- Moving to 6G and Above 100 GHz,” IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.
[22] https://ieeetv.ieee.org/event-showcase/brooklyn5g2018

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)



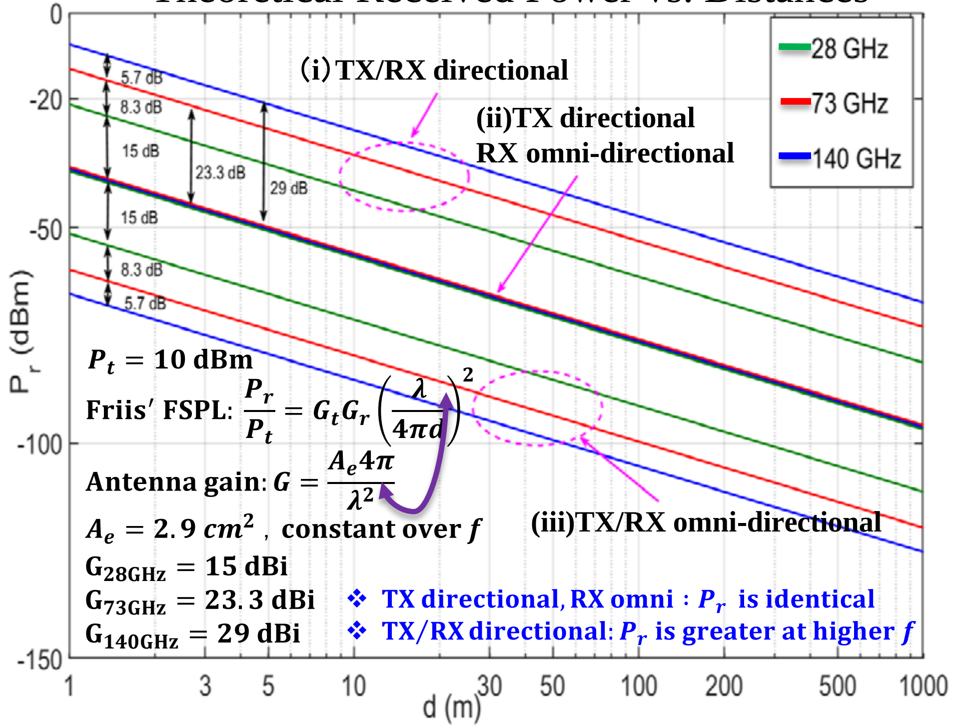
As expected, FSPL at 140/73/28 GHz follows the Laws of Physics and satisfies Friis' equations with antenna gains removed.

[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

NYU | TANDON SCHOOL OF ENGINEERING — NYU WIRELESS

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

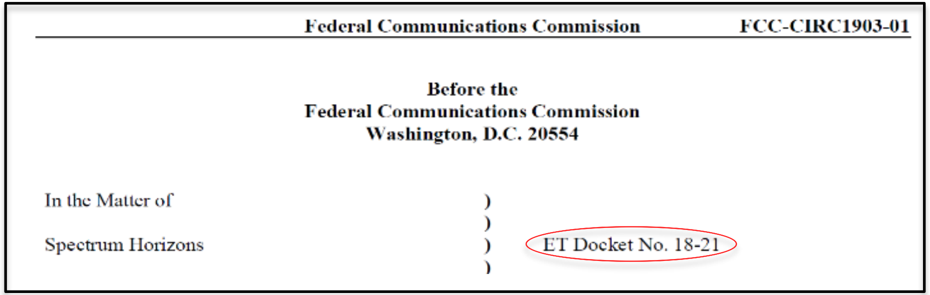
DIRECTIONAL ANTENNAS WITH EQUAL APERTURE HAVE MUCH LESS PATH LOSS AT HIGHER FERQUENCIES ([24] Ch.3 Page 104) !!!

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.

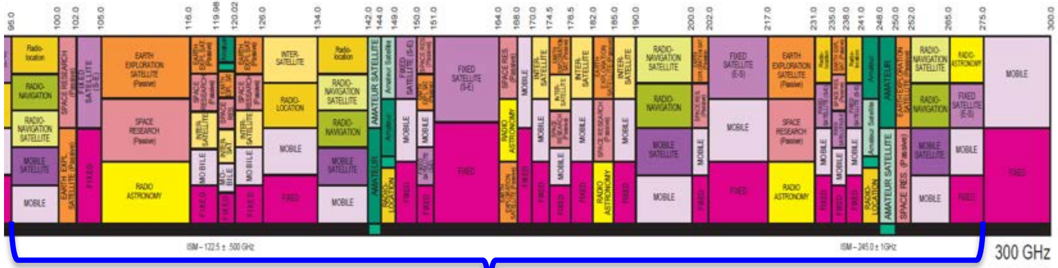
FCC opens above 95 GHz


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
Feb 22, 2019



95 GHz

275 GHz

40 frequency bands

- NYU WIRELESS first university in the mmWave Coalition- pushed for rules > 95 GHz
- Experimental licenses for 95 GHz to 3 THz - **Spectrum Horizons ET Docket 18-21**
- 21.2 GHz **Unlicensed Spectrum** to be allocated.
- Rules on Licensed spectrum deferred until sufficient technical and market data is obtained (NYU Thurst area)

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

Spectrum Policy Leadership

ET DOCKET 18-21 SPECTRUM HORIZONS

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 Approved on March 15th 2019

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

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?

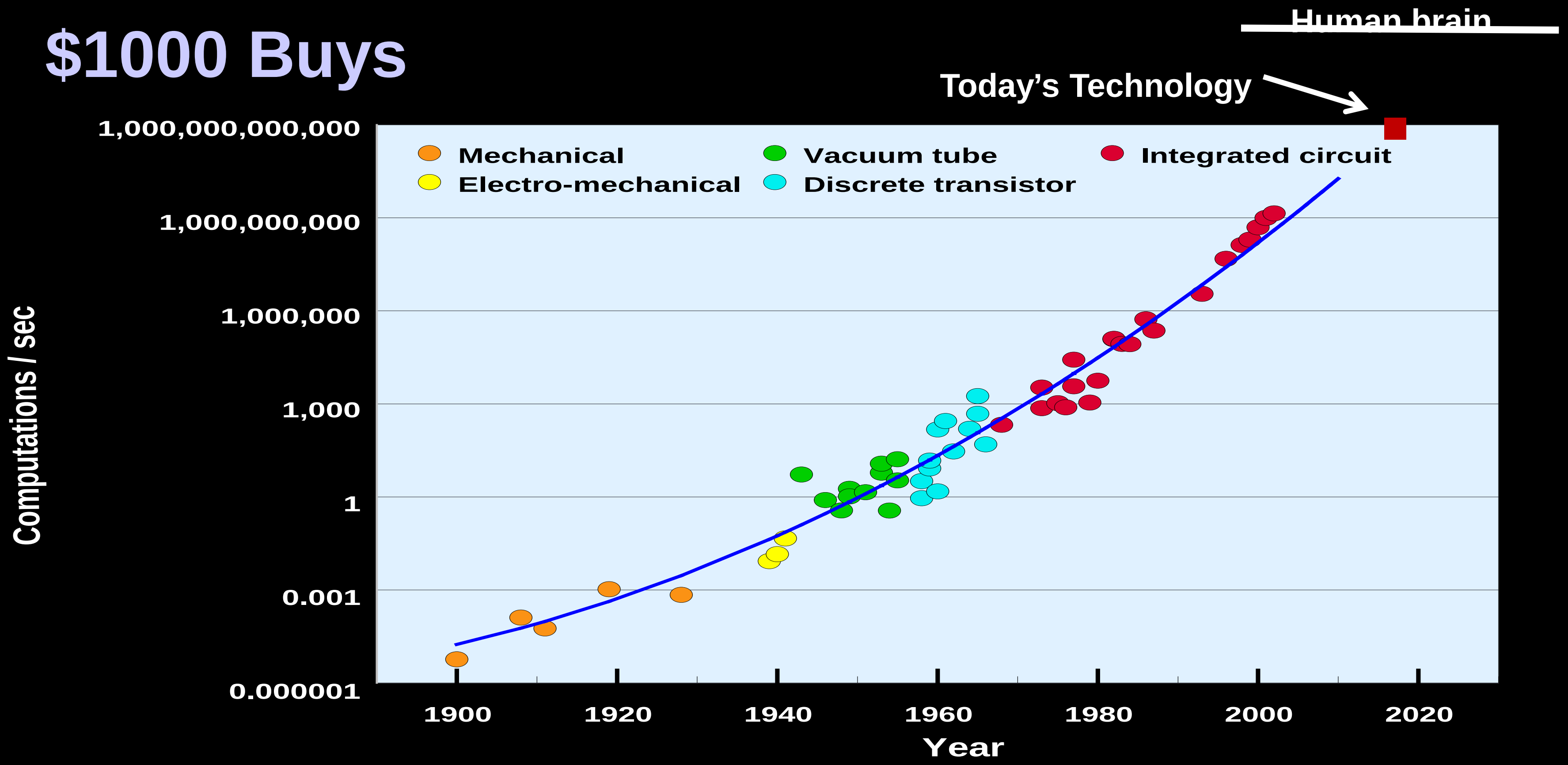
- 100 billion neurons
  Fire 200 times per second (5 milliseconds)

- Each neuron connected to 1000 others

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

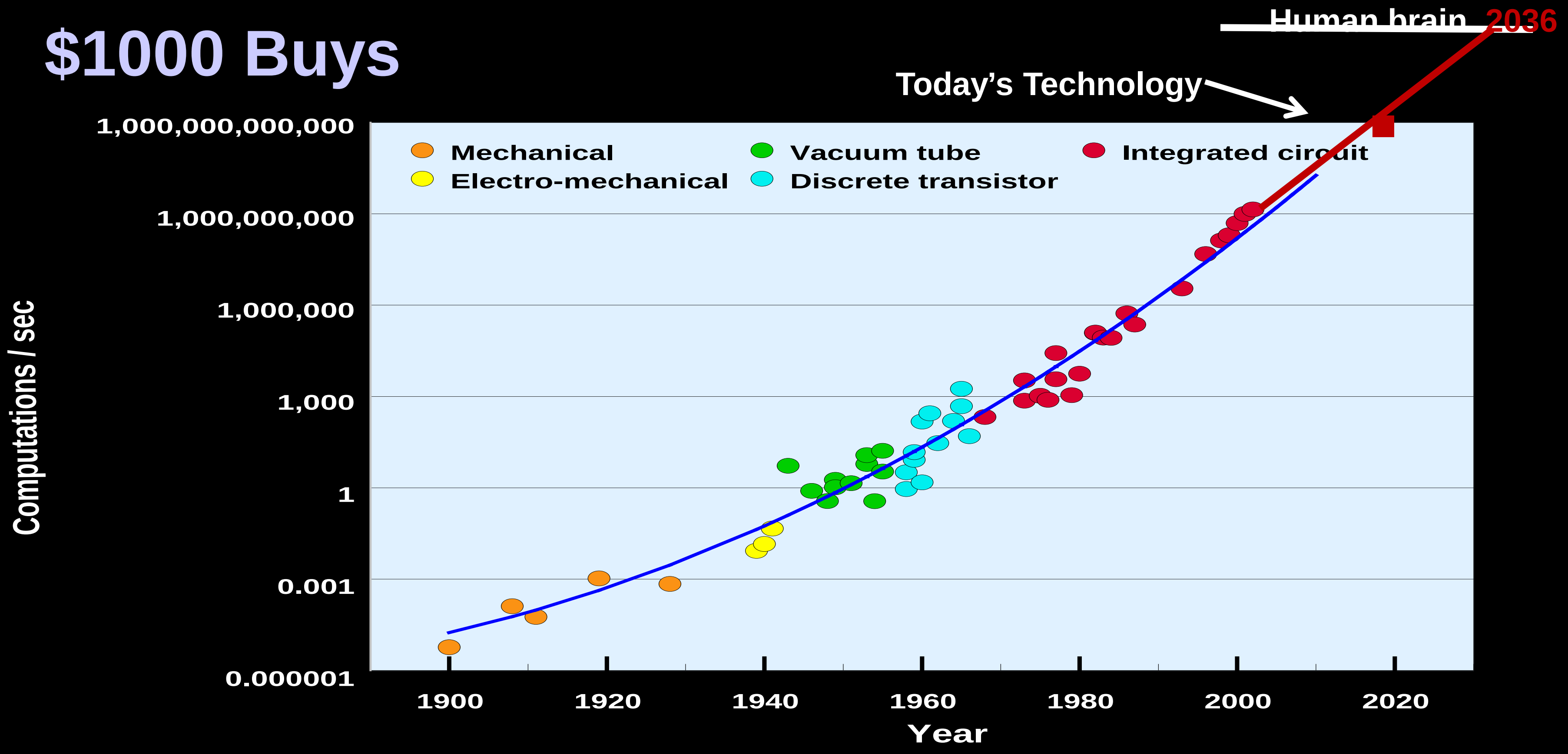
- Each neuron has write access to 1000 bits
  Storage = $(10^{11}) \times (10^{3}) = 10^{14} = 100 \times 10^{6} \times 10^{6}$
  =100 million megabytes = 100 terabytes

$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

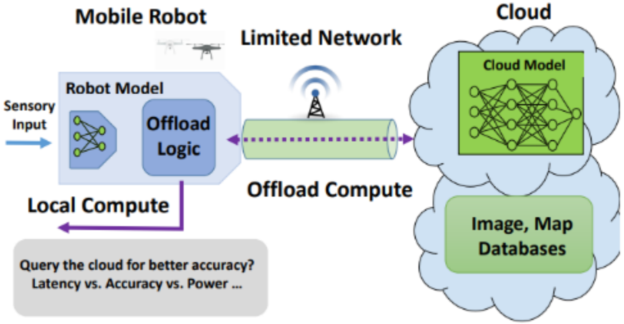
Applications Above 100 GHz

Autonomous cars

Drones Deliver

Robotics

Holographic Imaging and Spatial cognition



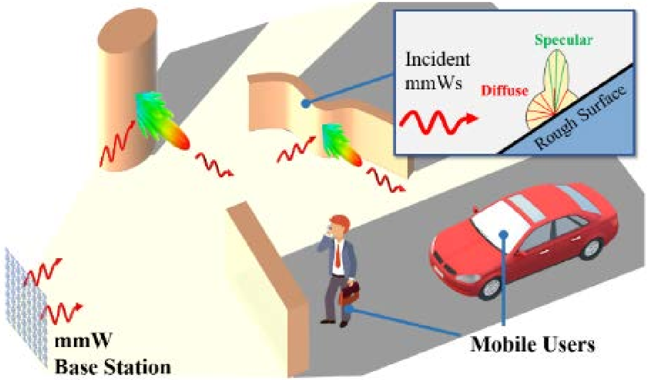
Wireless Cognition (Network Offloading) [17]

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

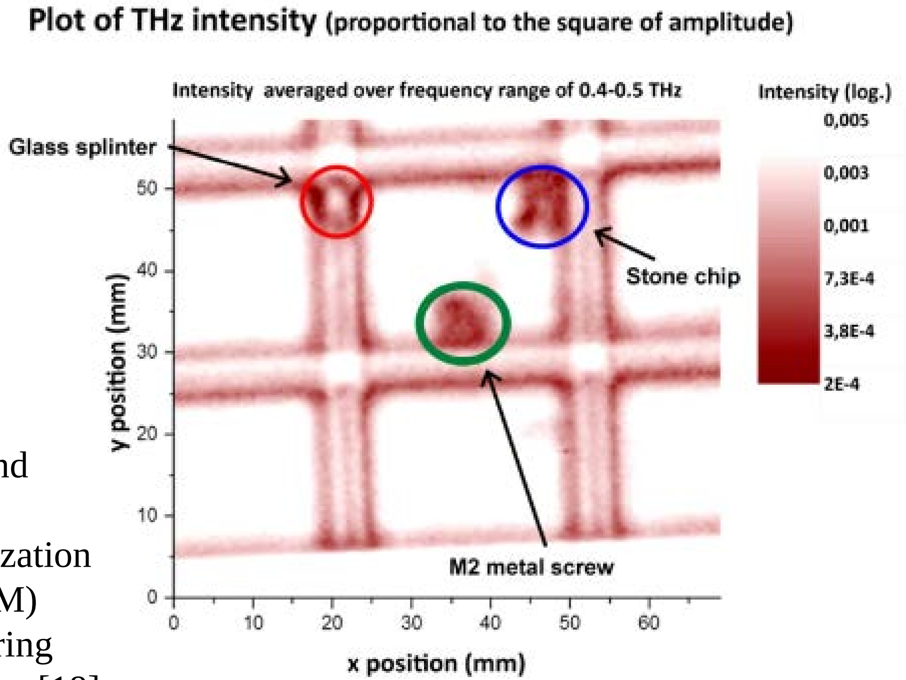
[17] Chinchali S. et. al., Network Offloading Policies for Cloud Robotics: a Learning-based Approach. arXiv preprint arXiv:1902.05703. 2019 Feb 15.

Applications Above 100 GHz

Body scanner using THz imaging to detect explosives [1]



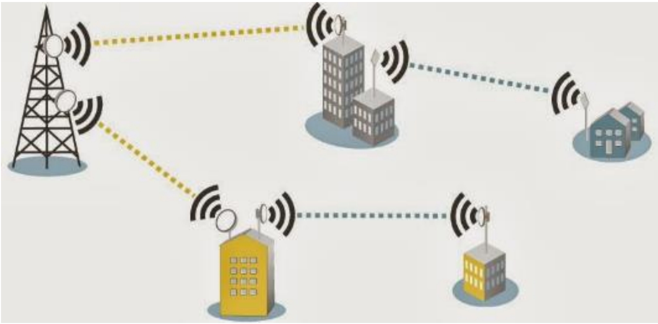
mmWave imaging and communications for Simultaneous Localization And Mapping (SLAM) exploiting the scattering properties at mmWave [18]



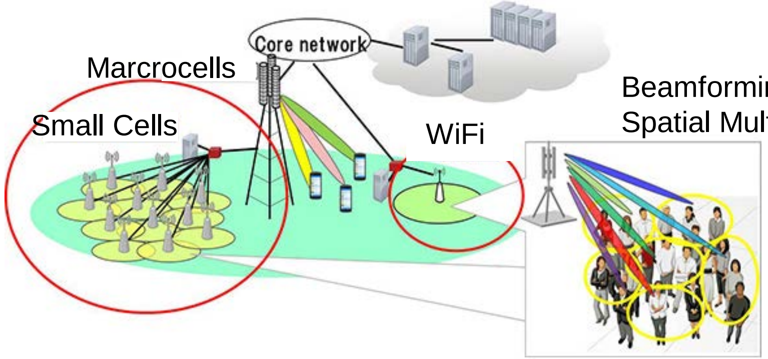
Glass, rock and a metal screw identified in a chocolate bar using THz imaging [17]

[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.

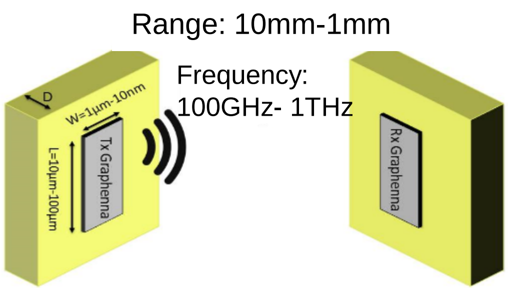
Applications Above 100 GHz



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



Mobile Communications [12]

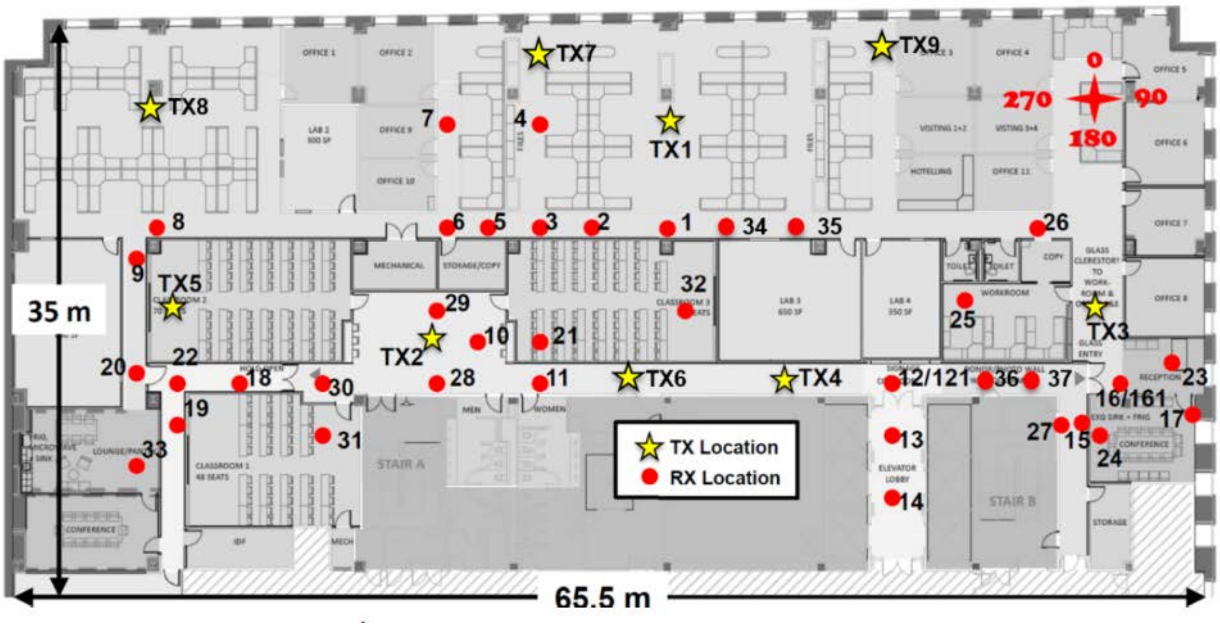


On-chip & chip to chip Terahertz communication links [20]

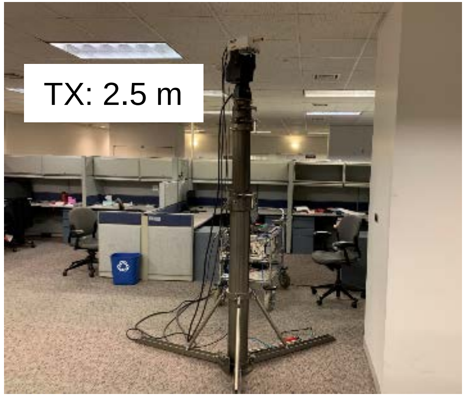
Short-range THz wireless connectivity in data centers [2]

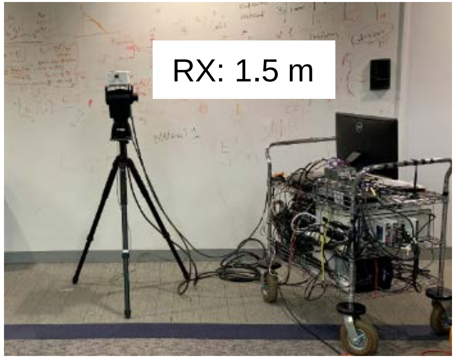
[2] http://terapod-project.eu/wp-content/uploads/2018/03/Re-imagining-data-centres-with-THz.pdf
[3] https://www.rfglobalnet.com/doc/fujitsu-develops-low-power-consumption-technology-for-g-0001
[12] T. S. Rappaport, et al., “Overview of millimeter wave communications for fifth-generation (5G) wireless 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 Channel Measurements



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].

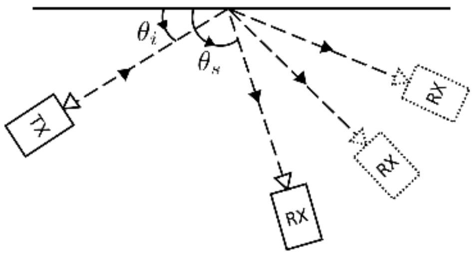


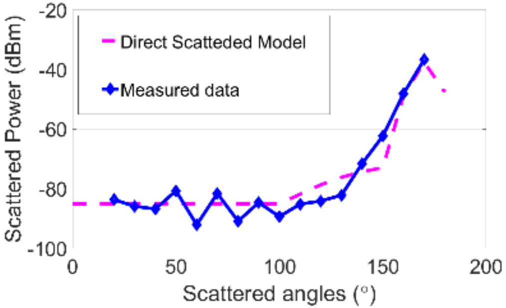


[25] G. R. Maccartney, T. S. Rappaport, S. Sun and S. Deng, "Indoor Office Wideband Millimeter-Wave Propagation Measurements and Channel Models at 28 and 73 GHz for Ultra-Dense 5G Wireless Networks," in *IEEE Access*, vol. 3, pp. 2388-2424, 2015.

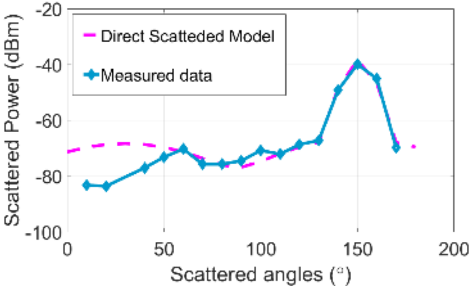
[21] Y. Xing and T. S. Rappaport, “Propagation Measurement System and Approach at 140 GHz-Moving to 6G and Above 100 GHz,” in IEEE 2018 Global Communications Conference, Dec. 2018, pp. 1–6.

Scattering Models at 140 GHz



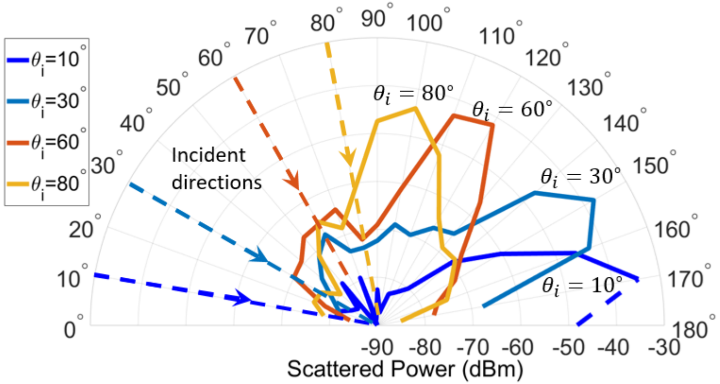


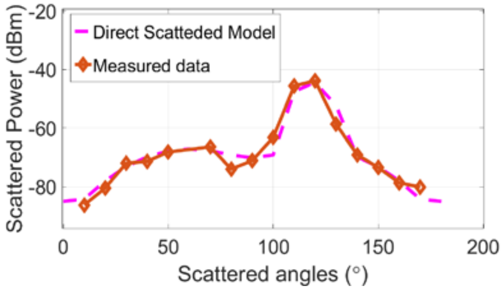
$\theta_i = 10°$



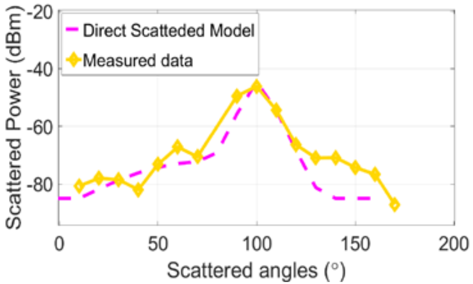
$\theta_i = 30°$

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].

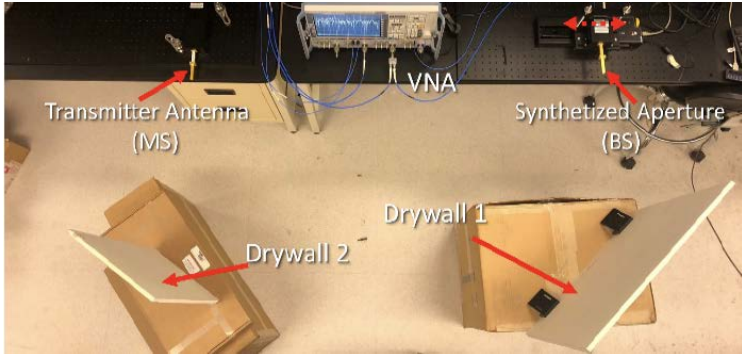
[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Alkhateeb, G. C. Trichopoulos, A. Madanayake, S. Mandal, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond (Invited)," IEEE ACCESS, submitted Feb. 2019.

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

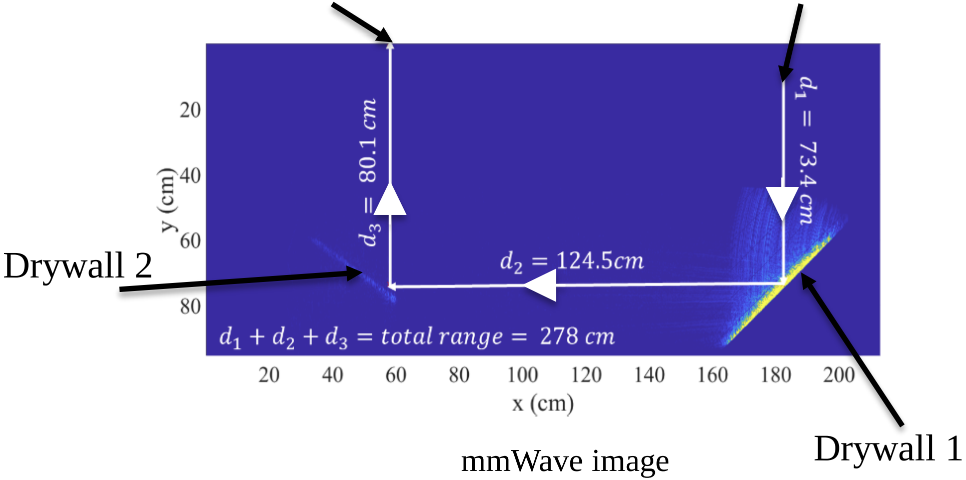
Tools for Localization

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



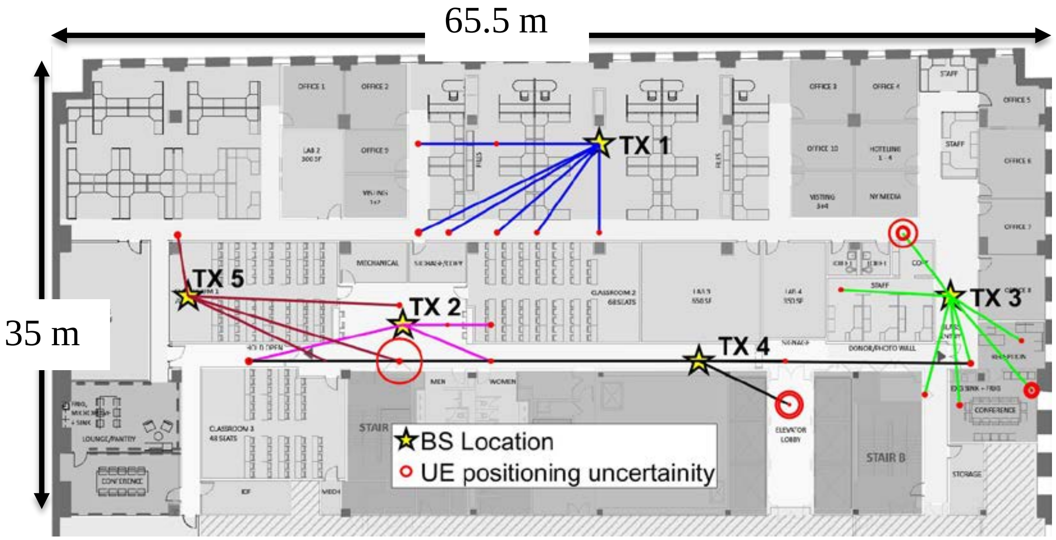
mmWave image

[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.

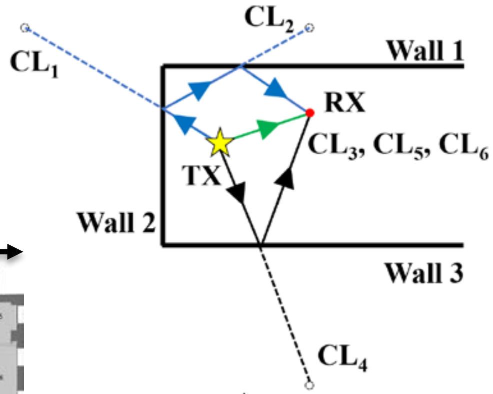
[18] M. Aladsani, A. Alkhateeb, and G. C. Trichopoulos, "Leveraging mmWave Imaging and Communications for Simultaneous Localization and Mapping," in International Conference on Acoustics, Speech, and Signal Processing (ICASSP), May 2019, pp. 1–4.

Models lead to Ray Tracing Tools

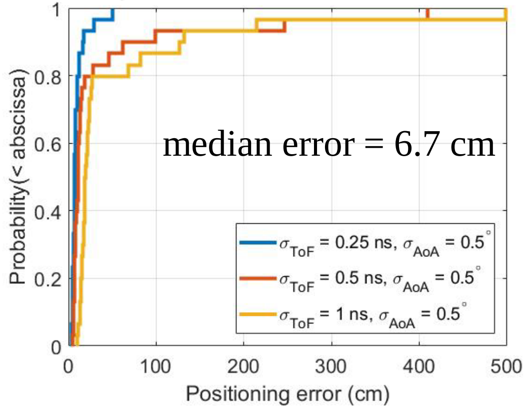
- cm-level localization with map, AoA, and ToF information at mmWave & THz, on-the fly in the phone or from edge [1].
- Materials ***not*** assumed to be perfect reflector at mmWave



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.

Results and Conclusions

- 5G has seen enormous progress since the “It Will Work!” paper in 2013
  - Global rollouts: engineers and technicians learning about mmWave and directional channels
  - Governments are creating spectrum opportunities

- Now is the time to work on 6G!

- Early work shows **clear sailing** up to 700 GHz!
- Mobile, fixed, sensing, position location, human cognition
- Wireless – NYU helped lead the world to mmW and now > 95 GHz

- THz Communications and Sensing at NYU WIRELESS
  - New uses cases: Aerial, robotics, see-in-the-dark imaging, bio/health monitoring
  - THz / Sub-THz Channel models, coverage/blockage/ planning tools for indoor/outdoor/penetration
  - Market Challenges: Power consumption, power efficiency, digital arrays, deployment tools and experience

Thank you!

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).

Thank You!

Addendum

- **Practical difficulties with mmW propagation penetrating into buildings**
- **Input that NYU WIRELESS gave FCC TAC in 2018 for Small Cells**
- **Selected References on 5G millimeter wave issues**
- **NYU WIRELESS Industrial Affiliates (Thank you Crown Castle)**

28 GHz Millimeter Wave Cellular Communication

Measurements for Penetration Loss in and around Buildings in New York City

Environment	Location	Material	Thickness (cm)	Received Power - Free Space (dBm)	Received Power - Material (dBm)	Penetration Loss (dB)
Outdoor	ORH	Tinted Glass	3.8	-34.9	-75.0	40.1
	WWH	Brick	185.4	-34.7	-63.1	28.3
Indoor	MTC	Clear Glass	<1.3	-35.0	-38.9	3.9
	WWH	Tinted Glass	<1.3	-34.7	-59.2	24.5
		Clear Glass	<1.3	-34.7	-38.3	3.6
		Wall	38.1	-34.0	-40.9	6.8

TABLE II
COMPARISON OF PENETRATION LOSSES FOR DIFFERENT ENVIRONMENTS AT 28 GHZ. THICKNESSES OF DIFFERENT COMMON BUILDING MATERIALS ARE LISTED. BOTH OF THE HORN ANTENNAS HAVE 24.5 DBI GAINS WITH 10◦ HALF POWER BEAMWIDTH

NYU WIRELESS, Rappaport, et. al. “Millimeter Wave Mobile Communications for 5G Cellular, it will work!” IEEE ACCESS Vol. 1, 2013

Key Regulatory Needs (1/4)

- ❖ **Great technology must be deployed rapidly and efficiently (time/$), This is VITAL for US competitiveness. Order last week is excellent first step, MUST PROCEED AGGRESSIVELY with Spectrum Auctions, 39 GHz needed quickly (24, 28 GHz good first step, but 39 GHz needed now)!**

- ❖ **Efforts are needed to streamline deployment and reduce fees for deployment of 5G technology in the Right of Way (ROW).**

- ❖ **Jurisdictions should only charge cost-recovery (not general revenue – be just like other public utilities) w/ non-discriminatory fees to access the ROW incl. municipal poles. No "hidden" broadband tax.**

- ❖ **Applications need review within FCC "shot clock" limits of 90 days (co-locations) and 120 days for new poles in ROW: Sec. 332 and 253.**

Key Regulatory Needs (2/4)

- ❖ Consider "overlashing" of new cables w/o application to pole owner

- ❖ Ensure pole owners follow the Commission's intended pole-attachment processes and timelines (pole owners use delay w/pre-applications – these delays and lack of clarity hurt deployment/plans). Amend pole rule to follow wireless Shot Clock and Section 6409 rules.

- ❖ Have timeline start immediately upon submission of a request for access. This will prevent utilities from evading Commission timelines.

- ❖ Pole owners (investor owned utilities, ILECs, etc.) need to break down costs for fair disputes, as carriers/infrastructure companies want to avoid legal complaints.

Key Regulatory Needs (3/4)

- NPRM 17-79 and 17-84: FCC should adopt a best practice for all carriers and infrastructure players. Example: Automated databases and notifications systems, such as those provided by National Joint Utilities Notification System (NJUNS) as a “best practice” for all utilities and attaching parties.

- Key FCC regulation for Interference, Adjacent Channel Leakage Radiation Power (ACLR), Adjacent Channel Selectivity (ACS): EIRP and OOBE still defined as an isotropic radiator in FCC rules. Using directional radiation requires massive overkill (cost and size/weight) for filtering to meet isotropic requirements over a directional array. FCC should adopt directional RF emission parameters (beamwidth dependent) rather than Isotropic for OOBE, ACLR, ACS, etc.

Key Regulatory Needs (4/4)

- Consider relaxation of wireless power charging rules for devices. 5G CPE and UE devices have lower RF power efficiency at mmWave, and thus may require higher power levels for battery charging than today's CPE/UE devices. Higher electromagnetic fields created by the charging coils may be needed.

- Jurisdictions need to relax control of locations: 5G small cells will have lower antenna heights, making it more critical to precisely place antennas for proper RF coverage at mmWave. Moving the antenna "a couple of poles away" can completely change the coverage of the site. FCC should enable proper placement without undue delays.

- Avoid zoning if infrastructure falls within a specific physical size or within a prescribed acceptable aesthetic footprint.

Selected References

[1] 3GPP, "Coordinated multi-point operation for LTE physical layer aspects," 3rd Generation Partnership Project (3GPP), TR 36.819 V11.2.0, Sep. 2013.
[2] D. Lee et al., "Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges," IEEE Communications Magazine, vol. 50, no. 2, pp. 148–155, Feb. 2012.
[3] S. Schwarz and M. Rupp, "Exploring coordinated multipoint beamforming strategies for 5G cellular," IEEE Access, vol. 2, pp. 930–946, 2014.
[4] M. Sadek et al., "A leakage-based precoding scheme for downlink multiuser MIMO channels," IEEE Transactions on Wireless Communications, vol. 6, no. 5, pp. 1711–1721, May 2007.
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[6] N. A. Muhammad et al., "Multi-cell coordination via disjoint clustering in dense millimeter wave cellular networks," in 2017 IEEE International Conference on Communications (ICC), May 2017, pp. 1–6.
[7] G. Zhu et al., "Hybrid beamforming via the kronecker decomposition for the millimeter-wave massive MIMO systems," IEEE Journal on Selected Areas in Communications, vol. 35, no. 9, pp. 2097–2114, Sep. 2017.
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[10] T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communications. Pearson/Prentice Hall 2015.
[11] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3rd Generation Partnership Project (3GPP), TR 38.901 V14.3.0, Dec. 2017.
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