Spectrum Frontiers:
The New World of Millimeter-Wave Mobile Communication

Professor Theodore (Ted) Rappaport
NYU WIRELESS
New York University Tandon School of Engineering

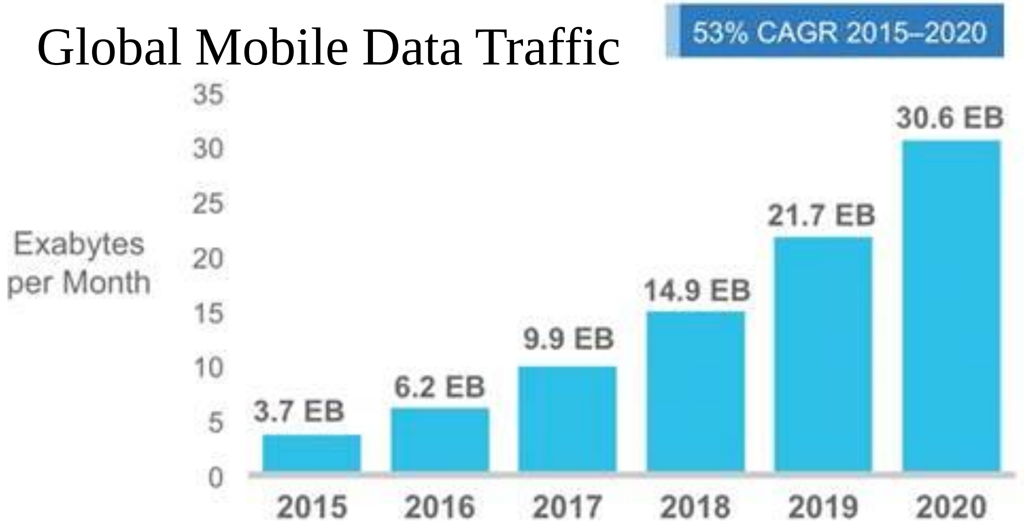
FCC Headquarters

March 10, 2016

Growing Traffic and Devices

http://www.nydailynews.com/news/world/check-contrasting-pics-st-peter-square-article-1.1288700

Global Mobile Data Traffic



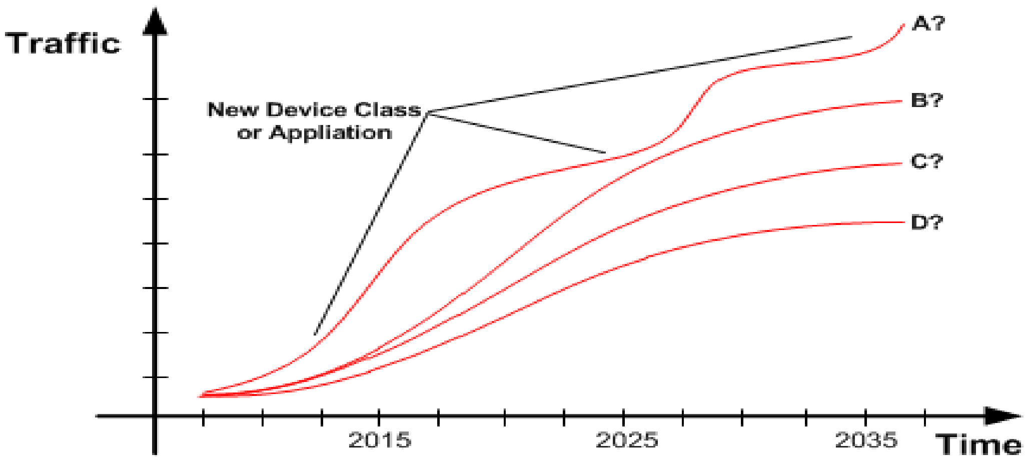
Source: Cisco Visual Networking Index (VNI) Mobile, 2016

Terabyte = 10^{12} Bytes
Petabyte = 10^{15} Bytes
Exabyte = 10^{18} Bytes

What Comes After Exabyte?

Cisco VNI forecasts annual global internet bandwidth consumption will reach 1.0 ***zettabytes*** in 2016 and 2.0 zettabytes by 2019. A zettabyte is equal to 1024 exabytes, which is ***one sextillion*** bytes. By 2020, global *mobile* IP traffic will reach an annual run rate of 367 exabytes, up from 44 exabytes in 2015.

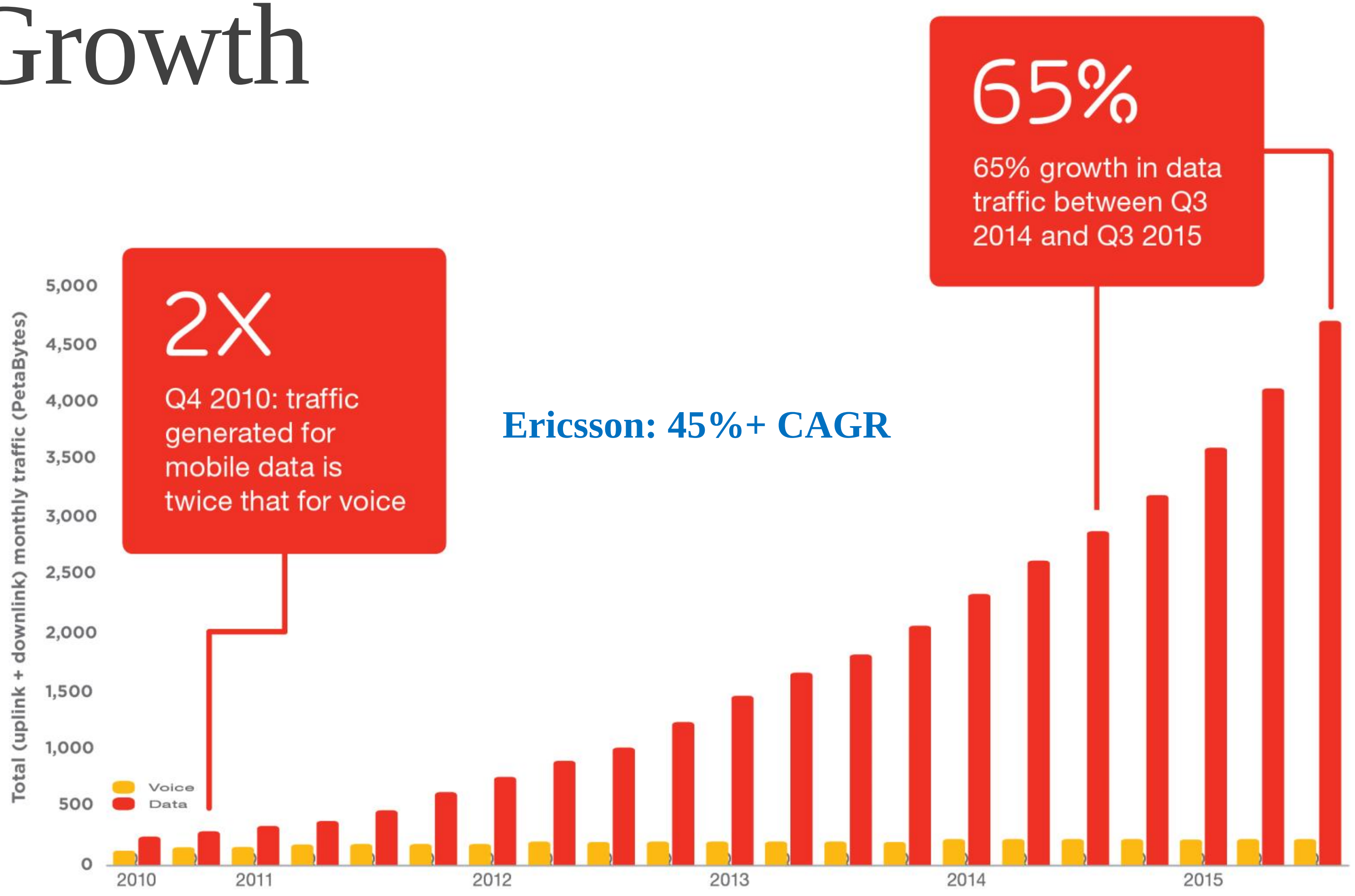
Mobile Traffic Growth



More "Realistic" Models

- New Users Are Not "Power Users"
- Modified Rate Plans
- Innovation Bursts

Source: Intel, Sept. 2013



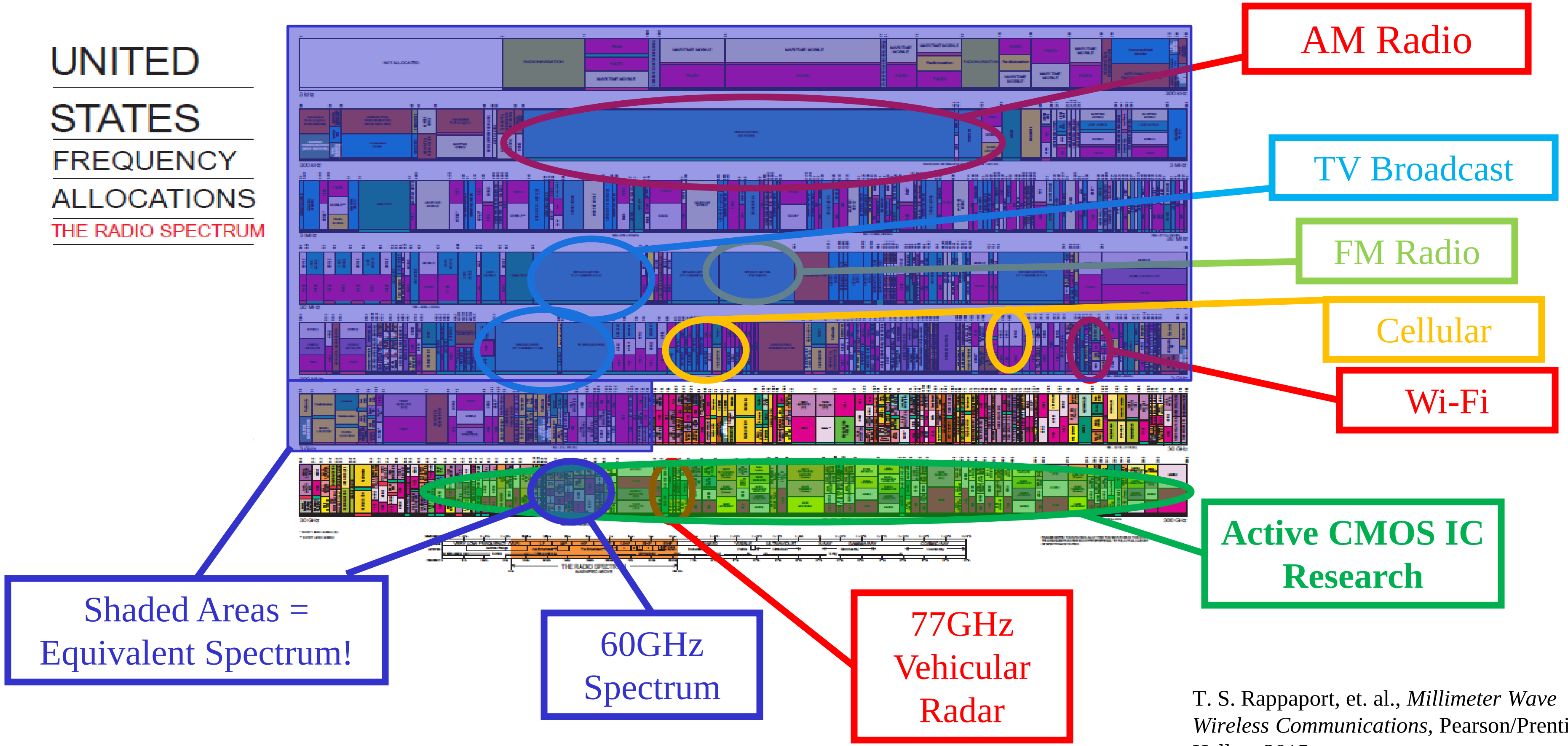
Source: Ericsson Traffic Measurements (Q4 2015)
Excludes DVB-H, WiFi, or Mobile WiMax, VoIP is included in data traffic

Wireless Carrier Frequencies Have Not Kept Pace

Moore's Law in the Past 40 Years

	1976	2016	Increase
Personal Computer Clock Speed	1 MHz	5 GHz	5,000x
Personal Computer Memory Size	256 KB	500 GB	4,000,000x
Cellular Phone Carrier Frequency	850 MHz	2.5 GHz	**3x**

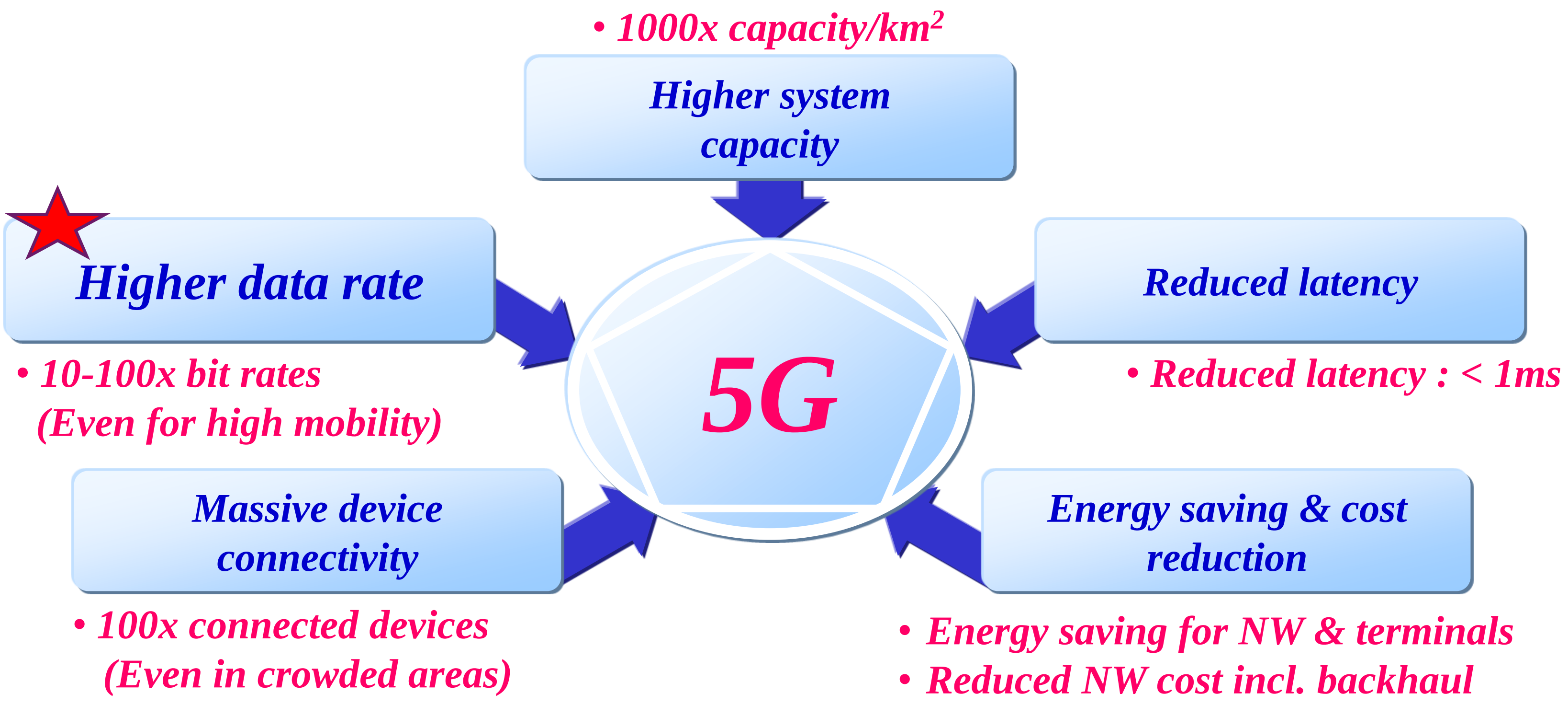
Spectrum: Key to Wireless Capacity



T. S. Rappaport, et. al., *Millimeter Wave Wireless Communications*, Pearson/Prentice Hall, c. 2015

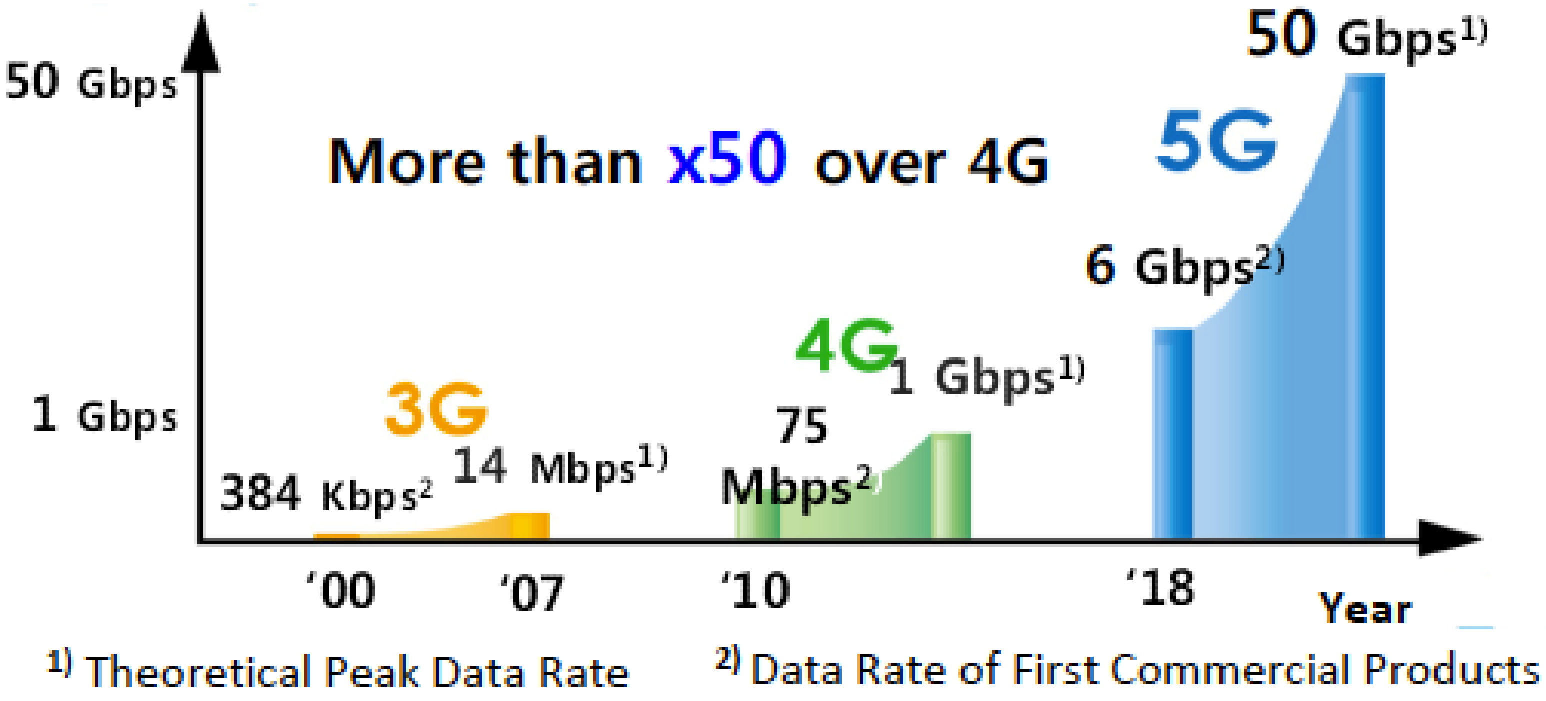
5G Requirements and Targets

DOCOMO 5G mobile communication



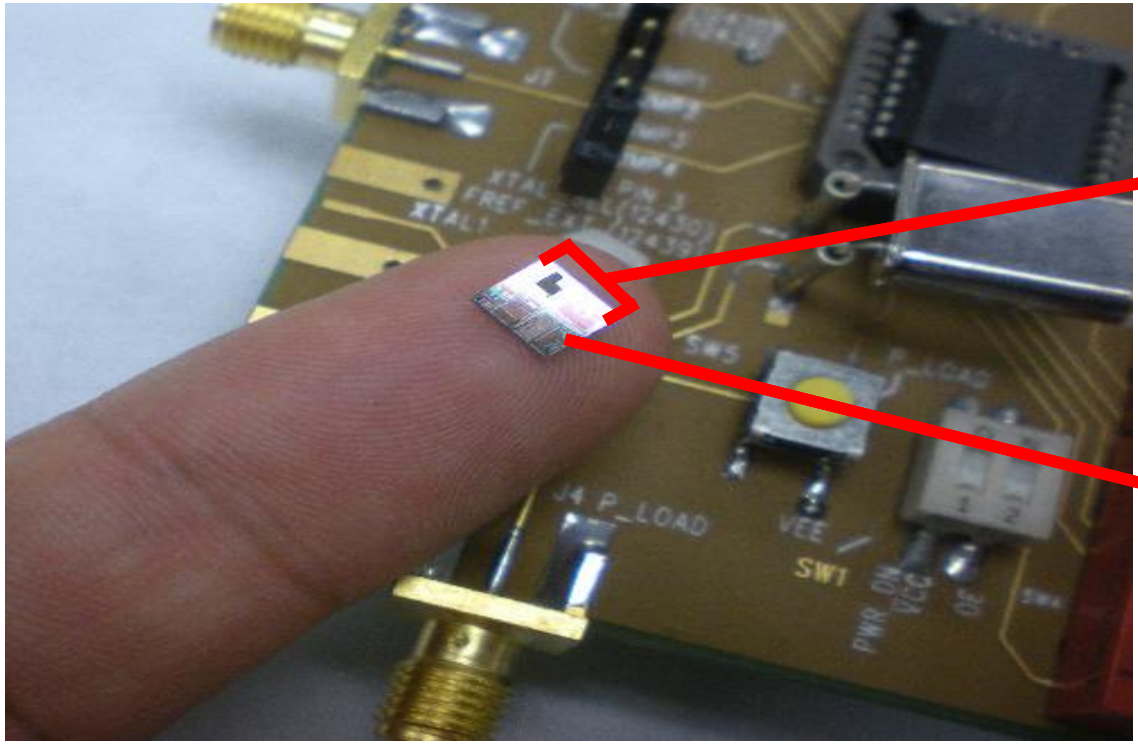
Source: TU3F-2 NTT DOCOMO, INC., Copyright 2014, All rights reserved. IMS2014, Tampa, 1-6 June, 2014

Wireless Data Rates per Generation

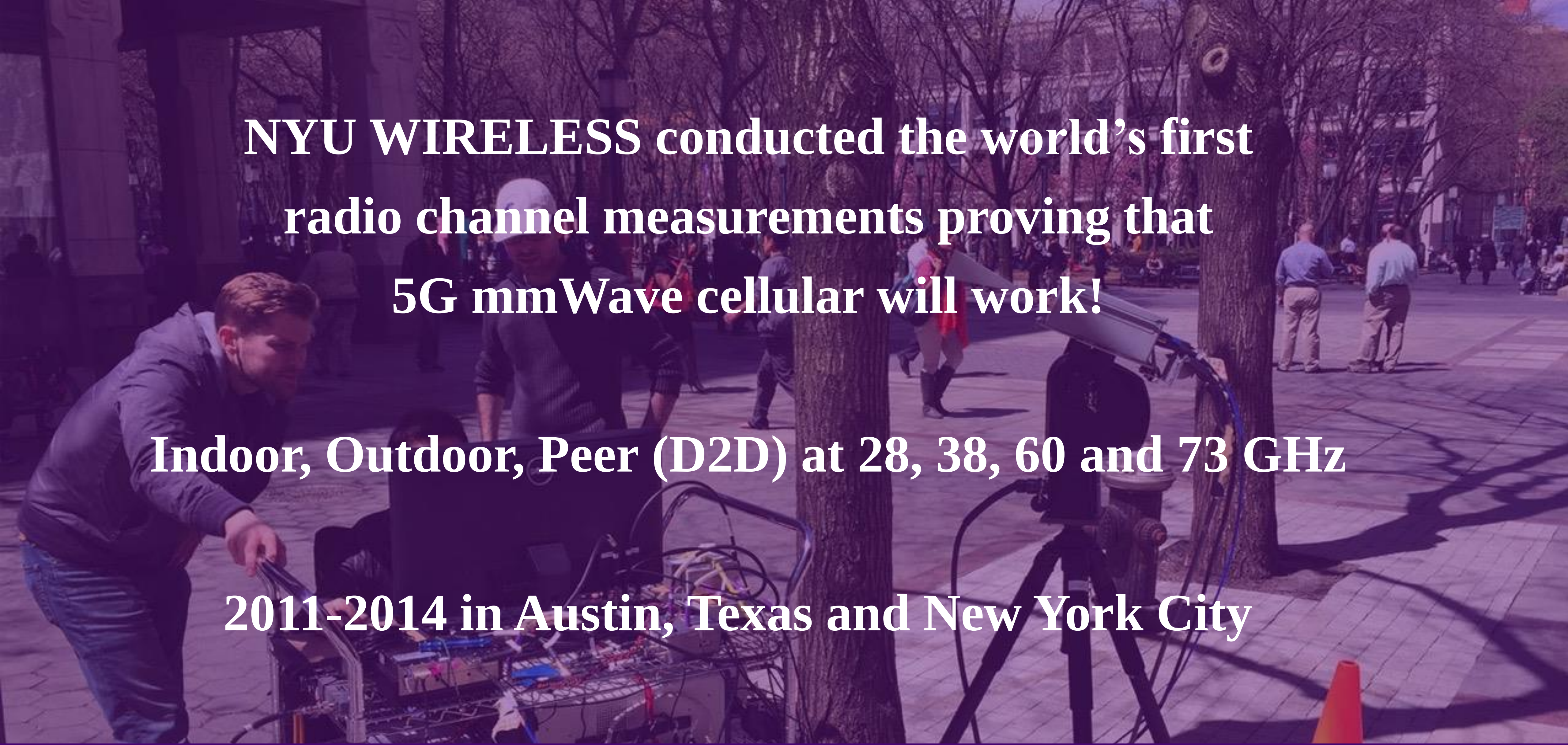


Plot of generational data rates for 3G, 4G, and 5G networks.
Millimeter Wave spectrum is needed to meet 5G demand .

mmWave Wavelength Visualization – 60 GHz



Source: F. Gutierrez, S. Agarwal, K. Parrish, and T.S. Rappaport, "On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems," IEEE Journal on Selected Areas in Communications, vol. 27, no. 8, October 2009, pp. 1367 – 1377.



NYU WIRELESS conducted the world's first radio channel measurements proving that 5G mmWave cellular will work!

Indoor, Outdoor, Peer (D2D) at 28, 38, 60 and 73 GHz

2011-2014 in Austin, Texas and New York City

T. S. Rappaport, et. al, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEE Access, No. 1, May 2013.

T.S. Rappaport, et. al., "Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications," IEEE Trans. Ant. Prop., Vo 61, No. 4, April 2013.

T. S. Rappaport, et. al, "Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design," IEEE Trans. Comm., Vol. 63, No. 9, Sept .2015.

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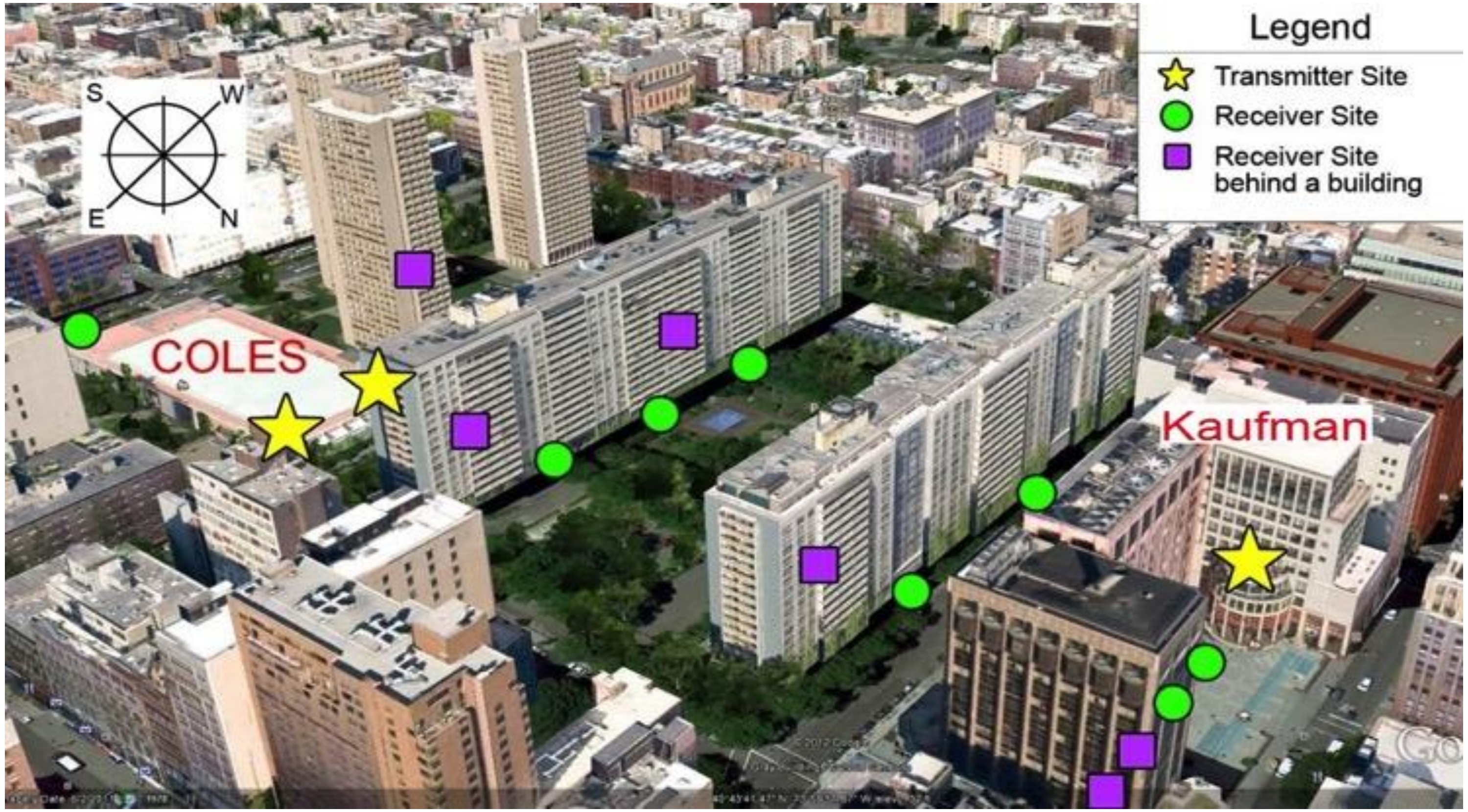
28 GHz Measurements in 2012
Dense, Urban NYC

- 4 TX sites
- 33 RX sites (35 w/ LOS)

- Pedestrian and vehicular traffic
- High-rise buildings, trees, shrubs

- TX sites:
  - TX-COL1 – 7 m
  - TX-COL2 – 7 m
  - TX-KAU – 17 m
  - TX-ROG – 40 m

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors in walkways



Rappaport, T.S.; Shu Sun; Mayzus, R.; Hang Zhao; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Gutierrez, F., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEEE *Access*, no. 1, pp.335-349, May 2013.

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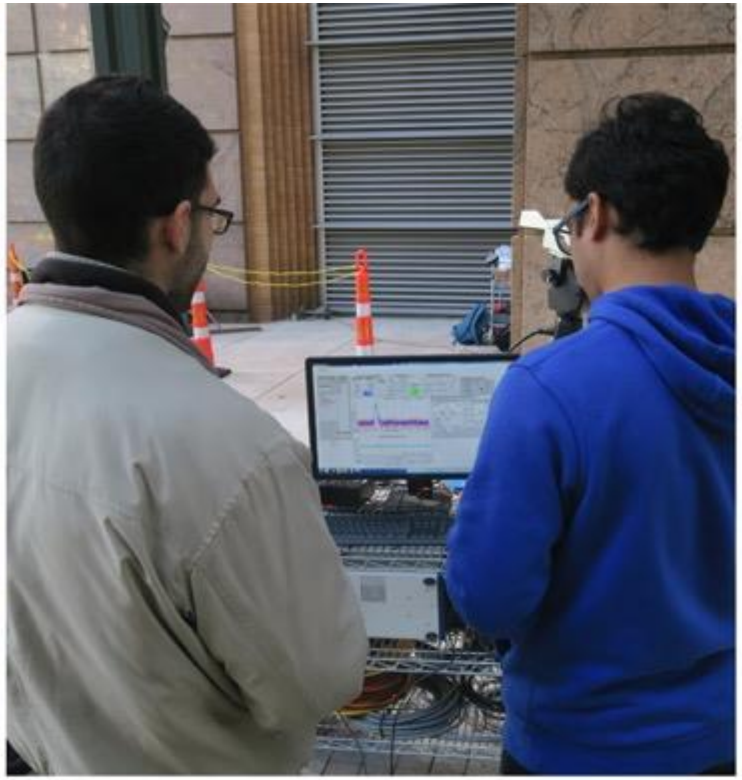
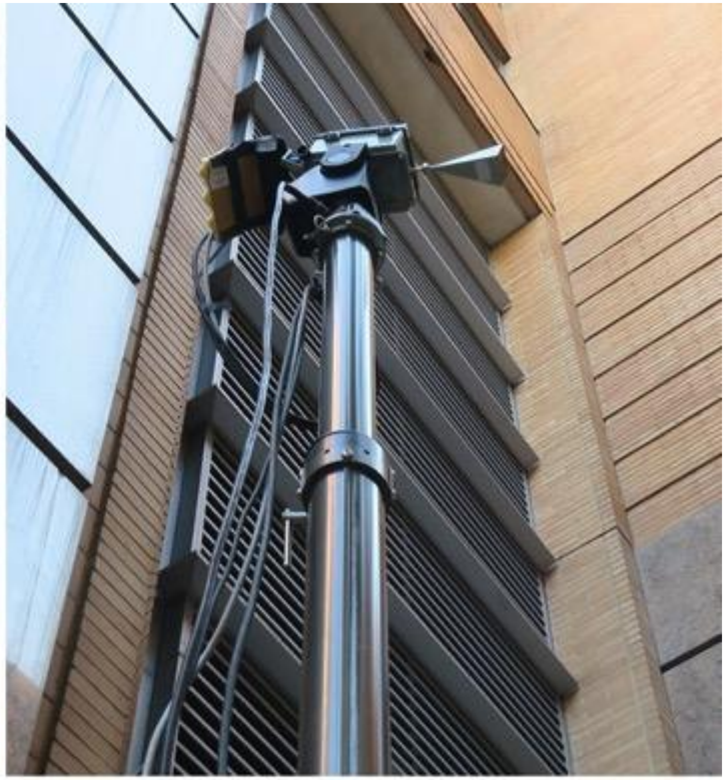
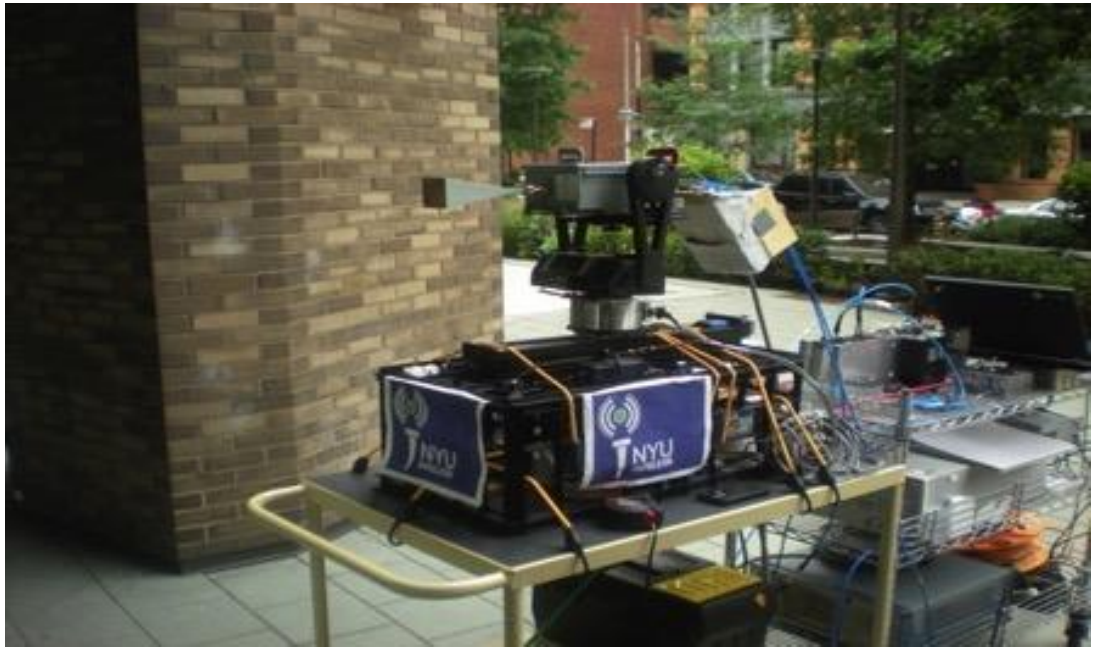



28 GHz Channel Sounder

TX Hardware



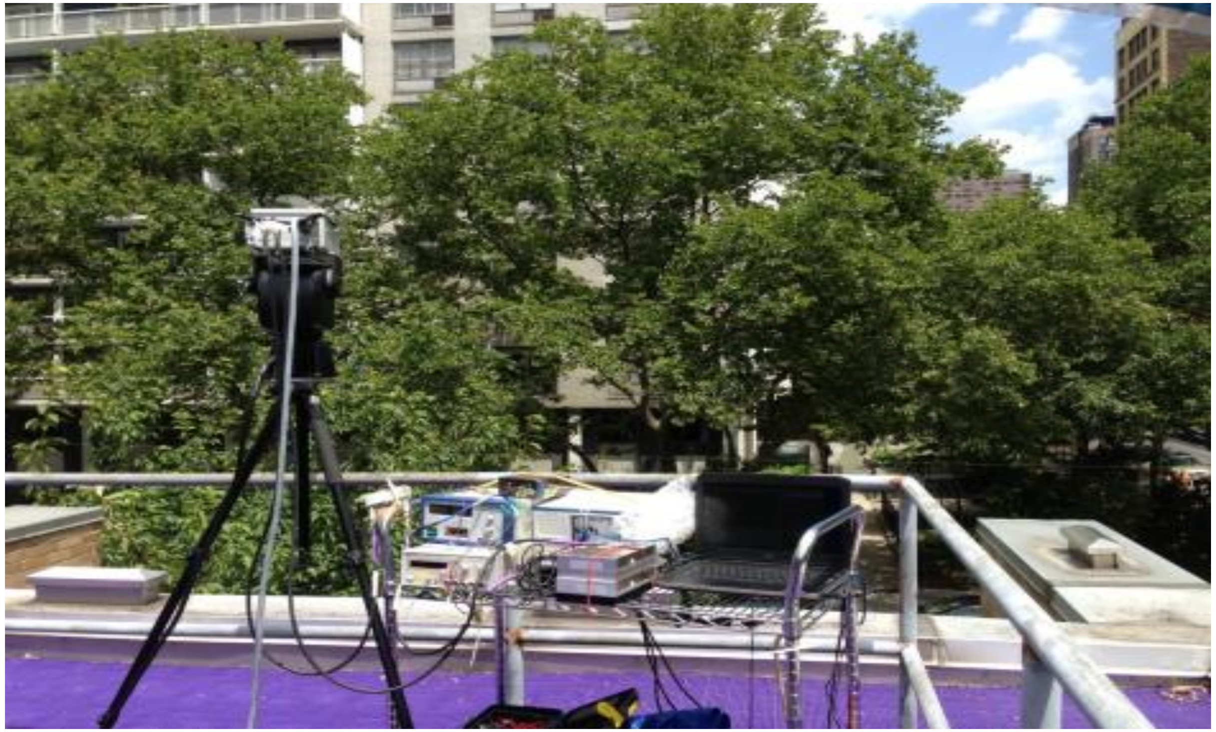
RX Hardware

Y. Azar, G. N. Wong, K. Wang, R. Mayzus, J. K. Schulz, H. Zhao, F. Gutierrez, D. Hwang, T. S. Rappaport, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," *2013 IEEE International Conference on Communications (ICC)*, June 9-13, 2013.

T.S. Rappaport,et. al.,"Wideband Millimeter Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design, IEEE Trans. Comm., Vol. 63, No. 9. Sept. 2015.

G.MacCartney, et. al., "Indoor Office Wideband Millimeter Wave Propagation Measurements and Channel Models at 28 and 73 GHz for ultra-dense 5G Wireless networks," IEEE Access, Vol. 3. November 2015.

73 GHz Channel Sounder



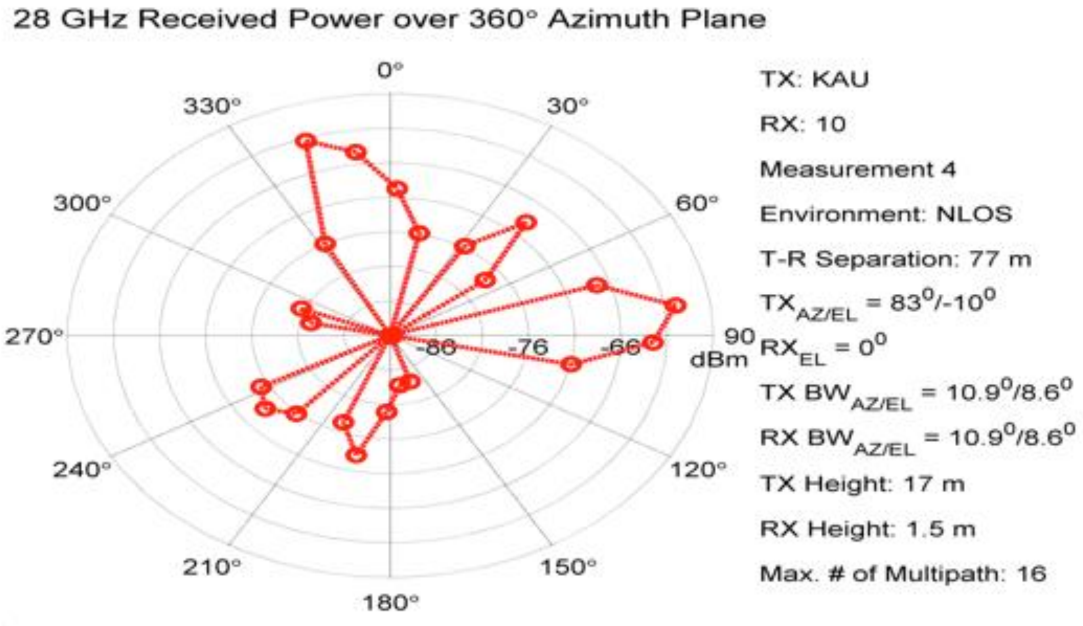
TX Hardware

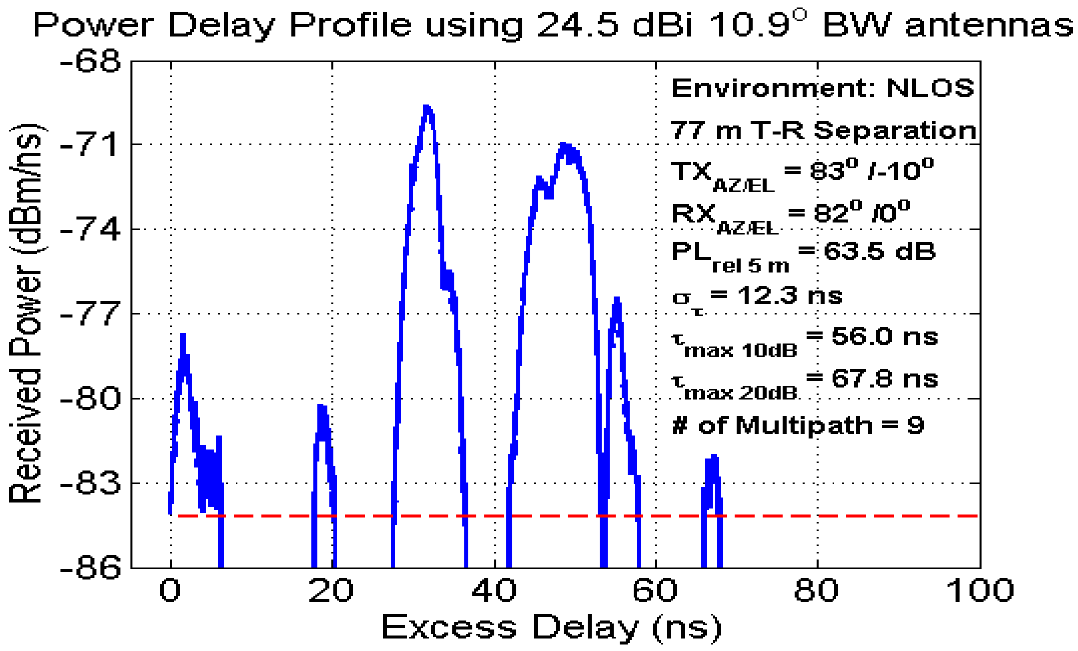
RX Hardware

T.S. Rappaport,et. al.,"Wideband Millimeter Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design, IEEE Trans. Comm., Vol. 63, No. 9. Sept. 2015.

G.MacCartney, et. al., "Indoor Office Wideband Millimeter Wave Propagation Measurements and Channel Models at 28 and 73 GHz for ultra-dense 5G Wireless networks," IEEE Access, Vol. 3. November 2015.

Measurements show Millimeter Wave is Revolutionary!





Signals arrive within 2 to 5 “lobes” in NYC over many azimuth angles in Non Line of Sight (NLOS)

Rappaport, T.S.; Shu Sun; Mayzus, R.; Hang Zhao; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Gutierrez, F., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," *Access, IEEE* , vol.1, no., pp.335,349, 2013

NYU WIRELESS Announces Open-source Simulation and Modeling Software Suite For Global Development of 5G Millimeter Wave Wireless Networks

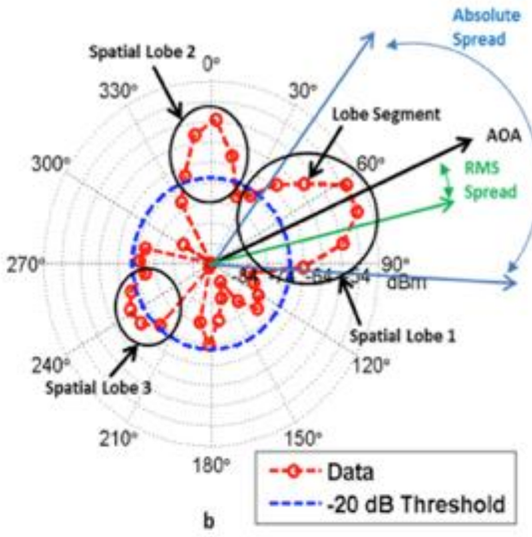
Downloads include real world data from 28 GHz and 73 GHz, and many resources

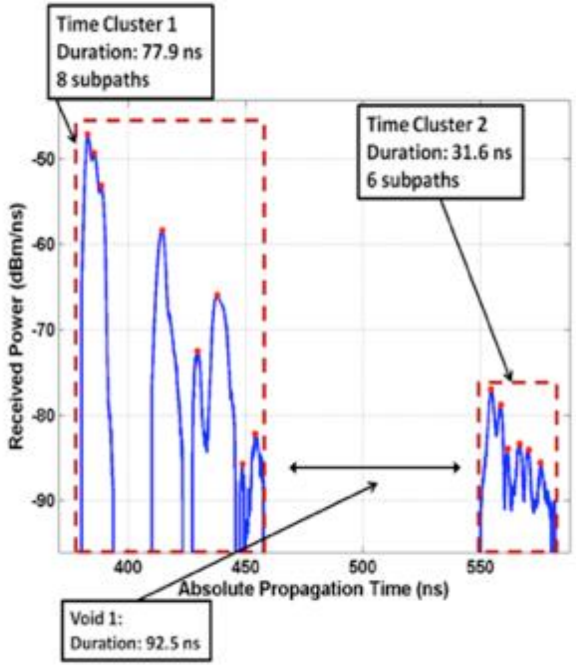
Now Publically Available:

http://nyuwireless.com/5g-millimeter-wave-channel-modeling-software/

or

http://bit.ly/1WNPpDX





M. Samimi, et. al., "3-D Statistical Channel Model for Millimeter-Wave," IEEE International Conf. on Communications (ICC), May 2015.

M. Samimi, et. al, "Statistical Channel Model with Multi-Frequency and Arbitrary Antenna Beamwidth for Millimeter-Wave Outdoor Communications, IEEE Global Communication Conf. (Globecom), Dec. 2015

M. Samimi, et. al, "Local Multipath Model Parameters for Generating 5G Millimeter-Wave 3GPP-like Channel Impulse Response," 2016 EuCap, April 2016.

The Renaissance of Wireless is at hand

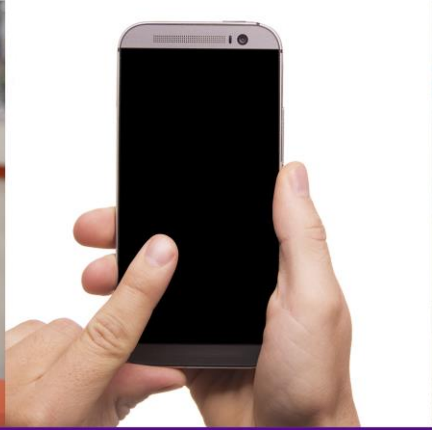
- mmW mobile offers 1000x capacity over 4G/LTE
- Experimental confirmation in NYC, Texas in 2011-2014
  - 200 m cell radius very feasible using only 1 Watt
  - Much greater range (>450 m) through beam combining
  - Simulations show multi-Gbps mobile data is viable
  - See prototypes on exhibit at the FCC today
  - NYU WIRELESS announces Open-Source Statistical Spatial Channel Model software suite for 5G
  - Complete simulator, extensive resources, field data
  - http://nyuwireless.com/5g-millimeter-wave-channel-modeling-software/
  - http://bit.ly/1WNPpDX

Millimeter Wave Mobile Communication:
1000 times today's fastest 4G cellphone speeds!

Revolutionary Products and Services for the Consumer

Driverless Cars

Virtual Reality
on a Phone



Phones That
Can Project Media

Patient/Medical
Records & 2 Way Video

Information Showers

Internet of Things

Conclusion

• In the *massively broadband®* era, wireless networks will obviate print, magnetic media, content, and wired connections in revolutionary ways!

• In 40 years, cellular carrier frequencies have only increased by a *factor of three* (850 MHz to 2.5 GHz). FCC's *Spectrum Frontiers* begins to address the capacity demand, bringing Moore's Law to carrier frequencies.

• By 2018 we will have commercial products above 70 GHz and 20 Gbps speeds in 5G cellular networks.

• Millimeter Wave wireless communications will revolutionize the mobile industry – ushering in a new frontier with unthinkable advances.

massively broadband ® is the property of T.S. Rappaport

The Renaissance of Wireless is at hand

1,000,000,000,000,000,000,000,000 bytes

To Zettabytes…and beyond

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

at&t
CableLabs
ERICSSON
HUAWEI
intel
InterDigital
L3 communications
SiBEAM
NATIONAL INSTRUMENTS
NOKIA
QUALCOMM
SAMSUNG
STRAIGHTPATH
KEYSIGHT TECHNOLOGIES
CABLEVISION
UMC
XO communications
NSF