Millimeter Wave Wireless Communications: The Renaissance of Computing and Communications

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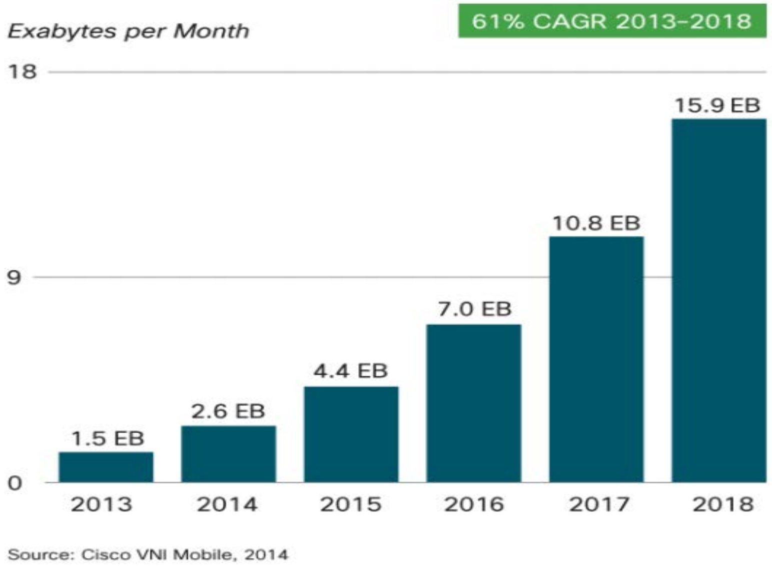
Keynote presentation
Sydney, Australia
June 13, 2014

Growing Traffic and Devices

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



CISCO, “Cisco Visual Networking Index: Mobile Data Traffic Forecast Update, 2013-2018,” 2014

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

Breaking News

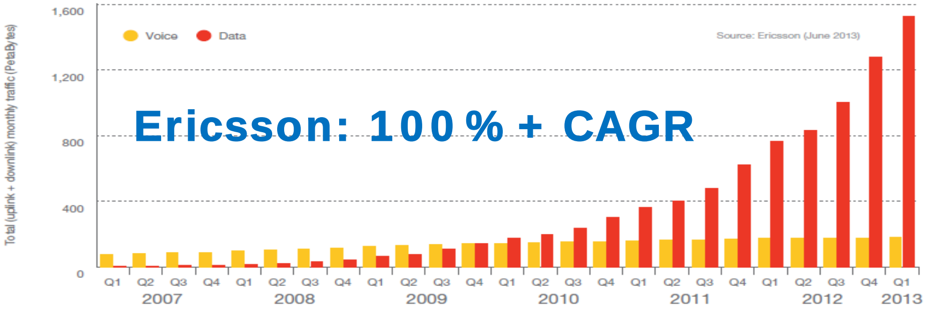
INTERNET NEWS. COM

2018 Internet Traffic to Top 1.6 Zettabytes

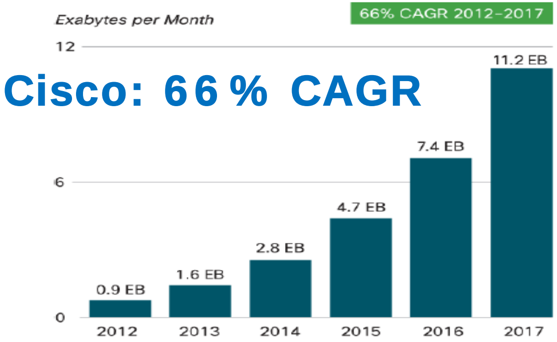
By Sean Michael Kerner | June 12, 2014

- For 2018, Cisco is now forecasting that bandwidth consumption will reach 1.6 zettabytes. In its 2013 VNI forecast, Cisco had predicted that bandwidth consumption in 2017 would reach 1.4 zettabytes. A zettabyte is equal to 1000 exabytes, which is one sextillion bytes.
- Even though the VNI forecast is a five-year projection for traffic, it isn't just a shot in the dark. Cisco has a sophisticated model for collecting data from multiple sources to obtain a high degree of forecast accuracy. Cisco had originally forecast traffic in 2013 to be 50 exabytes, while the actual number came in at 51 exabytes.

Mobile Data Traffic Growth



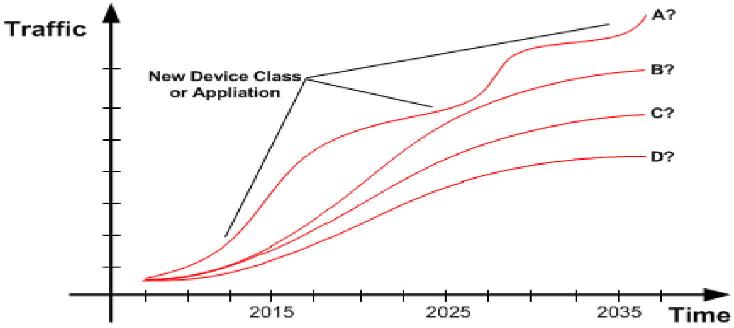
Ericsson Mobility Report, June 2013
Excludes WiFi, VoIP, MTC



Cisco Visual Networking Index, Feb. 2013

- **System Capacity Requirements**
  - Network traffic load increasing by **65-100% CAGR**
  - Requires up to **2x increase** in network capacity per annum
  - Relative to 2013 – assuming exponential growth[1] maintained
    - 2025 = **~1600** x 2013 load
    - 2040 = **16M** x 2013 load

Note 1: Assumes 85% CAGR in traffic.



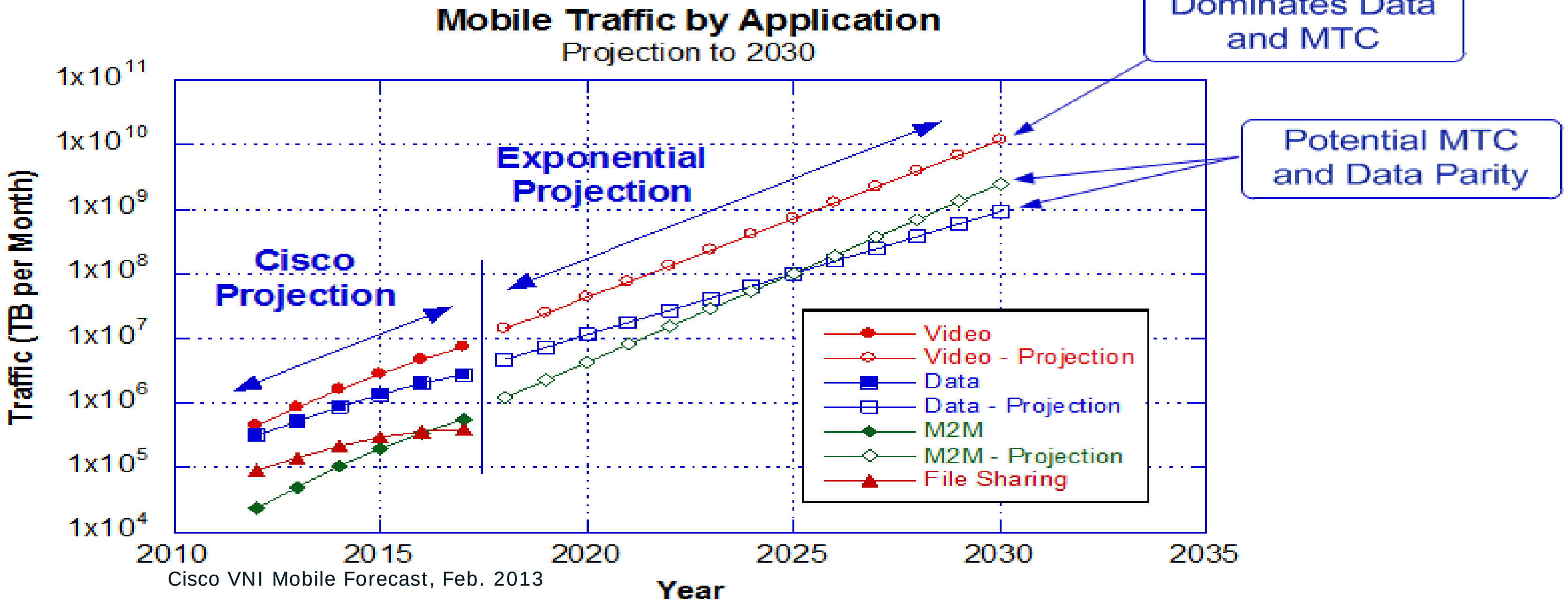
More "Realistic" Models

- New Users Less "Power User"
- Modified Rate Plans
- Innovation Bursts

Source: Intel, Sept. 2013

Traffic Growth – Video Dominance

Total Network Traffic - Video vs. MTC vs. Data

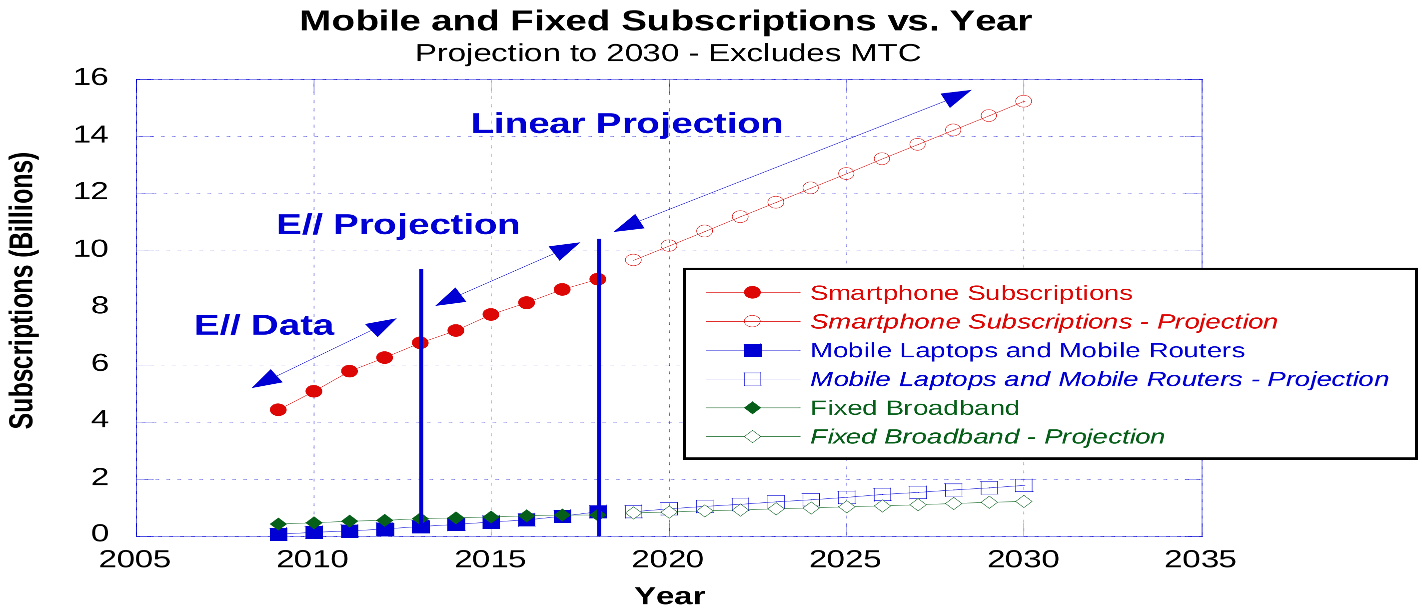


Conclusion: Optimize future wireless networks for video traffic regardless of RAT – but seek to retain high performance for MTC, HTTP, etc.

Source: Intel, Sept. 2013

Subscriber Growth – Smartphone Dominance

Global Mobile and Fixed Wireless 2010-2030



Ericsson Mobility Report, June 2013

Conclusion: Smartphone dominance continues, hence optimize future wide-area systems for smartphone base – but device innovation is disruptive….

Notes:

1. Excludes machine-machine (M2M) traffic.
2. H2H – human to human

Source: Intel, Sept. 2013

Wearable and LP Devices by Connectivity*

*NFC not included (only one device with NFC + BT connectivity)

Wi-Fi only	2
BT only	7
BLE only	6
Wi-Fi + BLE	1
BT + BLE	4
Wi-Fi + BT + BLE	2
Wi-Fi + BT + GNSS	1
Wi-FI + BLE + GNSS	1
Wi-Fi + BT + BLE + GNSS	2
Total Devices	**26**

Majority today connect using BT/BLE to a companion device

Source: Intel, Sept. 2013

- **Key Trends – 2013-2025**
  - **"Exponential" Traffic Growth Continues**
    - 100x+ by 2025 unless network capacity limits traffic
  - **Wireless Traffic Dominated by Video Multimedia**
    - Initially H.264, then H.265, delivered via A-HTTP/DASH protocols
  - **Expectation of Ubiquitous Broadband Access Strengthens**
    - Users expect and need wireless broadband *everywhere*
  - **Expectation of Gbps, Low Latency Access Strengthens**
    - Critically in dense traffic areas: enterprise, transport centers, stadia
  - **New Class of Internet of Things Devices Emerges**
    - Disparate class of devices – ranging from {very low-power, intermediated, very low rate} to {high power, direct, high rate}

30 More Years of Innovation, Growth and Revenue

Source: Intel, Sept. 2013

5G Requirements and Targets

DOCOMO 5G mobile communication

5G

Higher system capacity

- *1000x capacity/km²*

Higher data rate

- *10-100x bit rates (Even for high mobility)*

Reduced latency

- *Reduced latency : < 1ms*

Massive device connectivity

- *100x connected devices (Even in crowded areas)*

Energy saving & cost reduction

- *Energy saving for NW & terminals*
- *Reduced NW cost incl. backhaul*

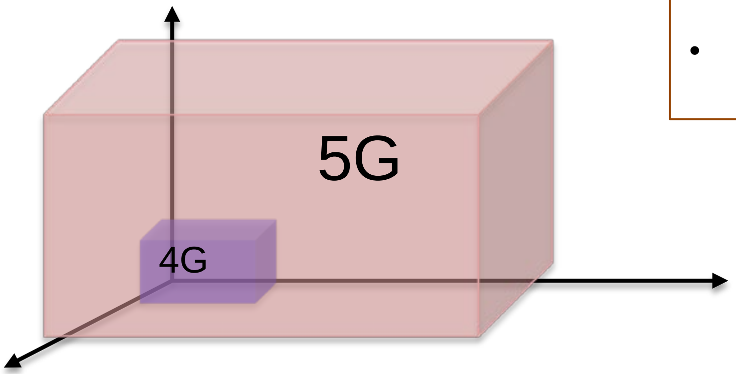
5G and 10,000x the bps/Hz/km^2: where will the gains come from?

Bandwidth (20x more Hz)

Only one place to go: mmWave
(Also LTE-U as stopgap)

mmWave + HetNets
- very complementary
- densifying mmWave cells yields huge gains (SNR plus cell splitting)
- Can possibly do self-backhauling!

mmWave + massive MIMO
- Some competition here
- Improved SINR via mmWave with high gain antennas, interference goes to zero?



***Effective* Density (50x More *Loaded* BSs/km^2):**

Efficient HetNets, small cell and WiFi offloading, maybe D2D

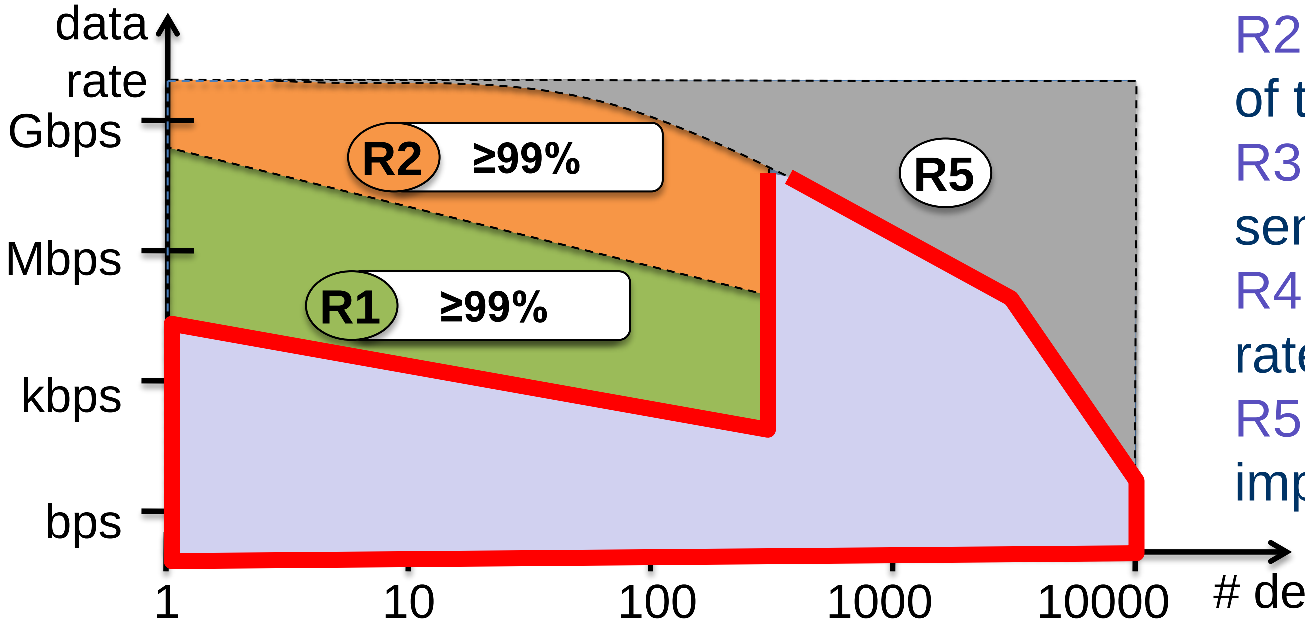
Spectral efficiency (10x more bps/Hz)

More dimensions (massive MIMO)
Interference suppression?

HetNets + massive MIMO
- HetNets may not be able to utilize massive MIMO
- Cost a key challenge here

Prof. J. Andrews, IEEE Comm. Theory Workshop, May 2014, Curacao

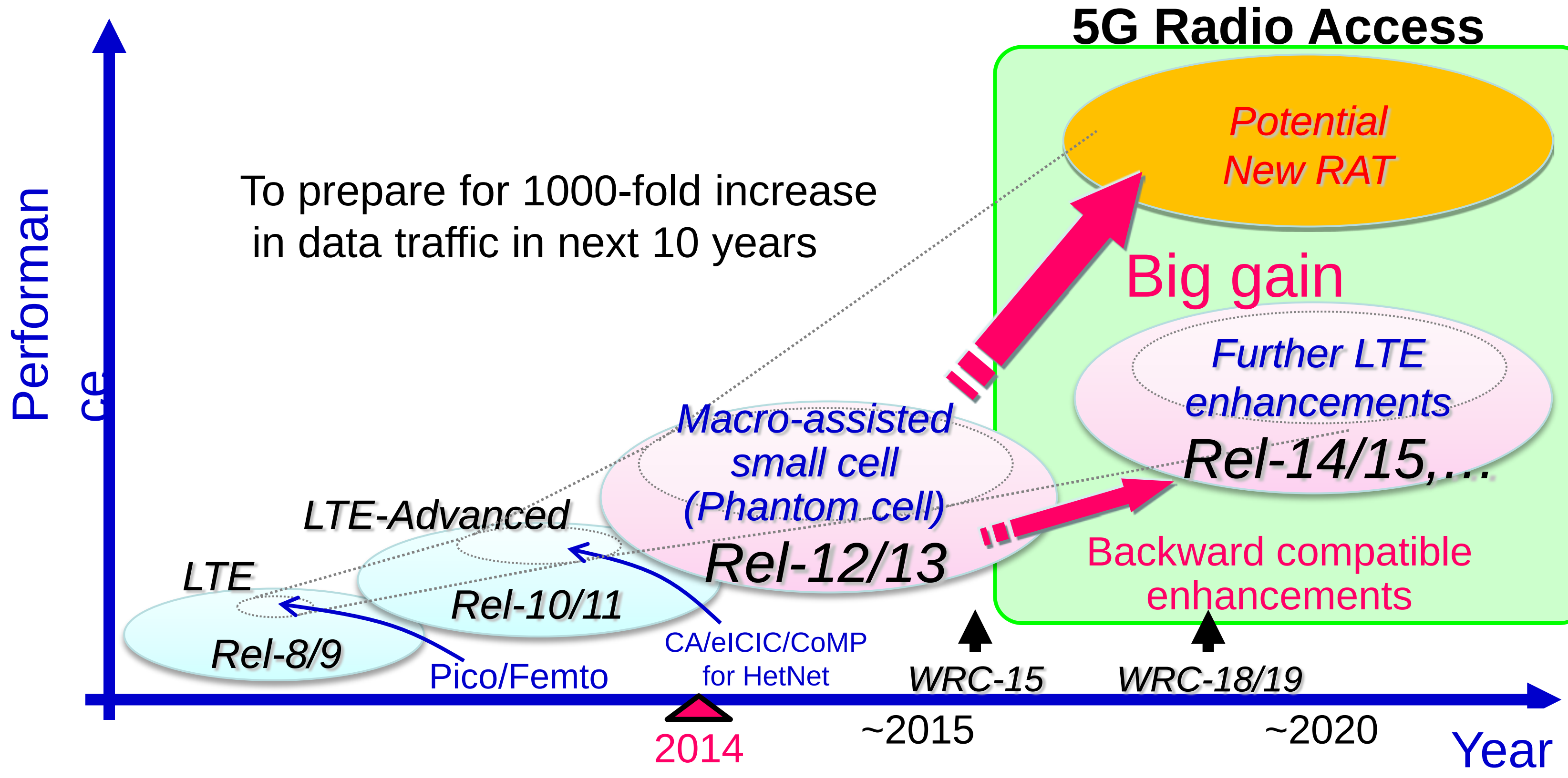
M2M-biased view on 5G



R1: today's systems
R2: high-speed versions of today's systems
R3: massive access for sensors and machines
R4: ultra-reliable low rate connectivity
R5: physically impossible?

F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five Disruptive Technology Directions for 5G", IEEE Communications Magazine, February 2014.

5G Radio Access Technology (RAT)



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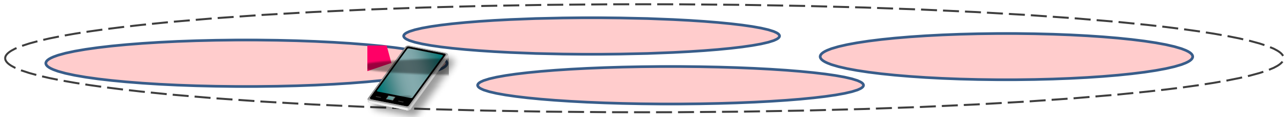
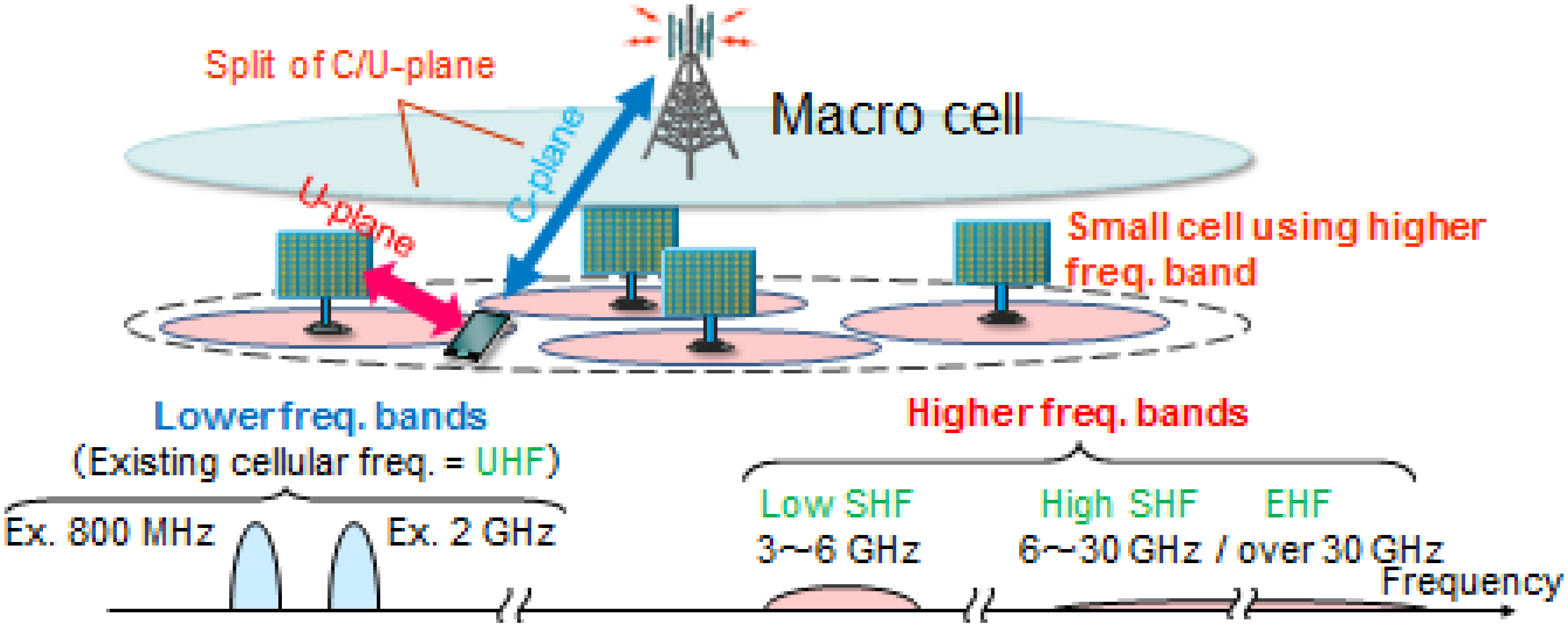
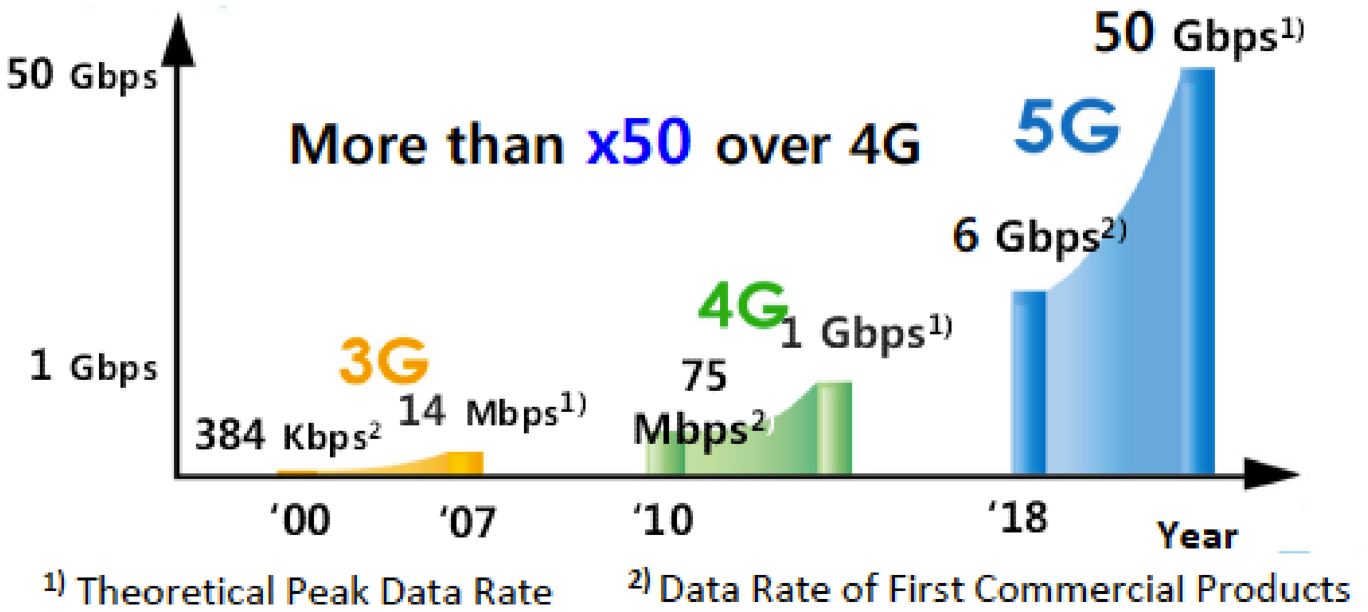


Phantom Cell Concept for 5G



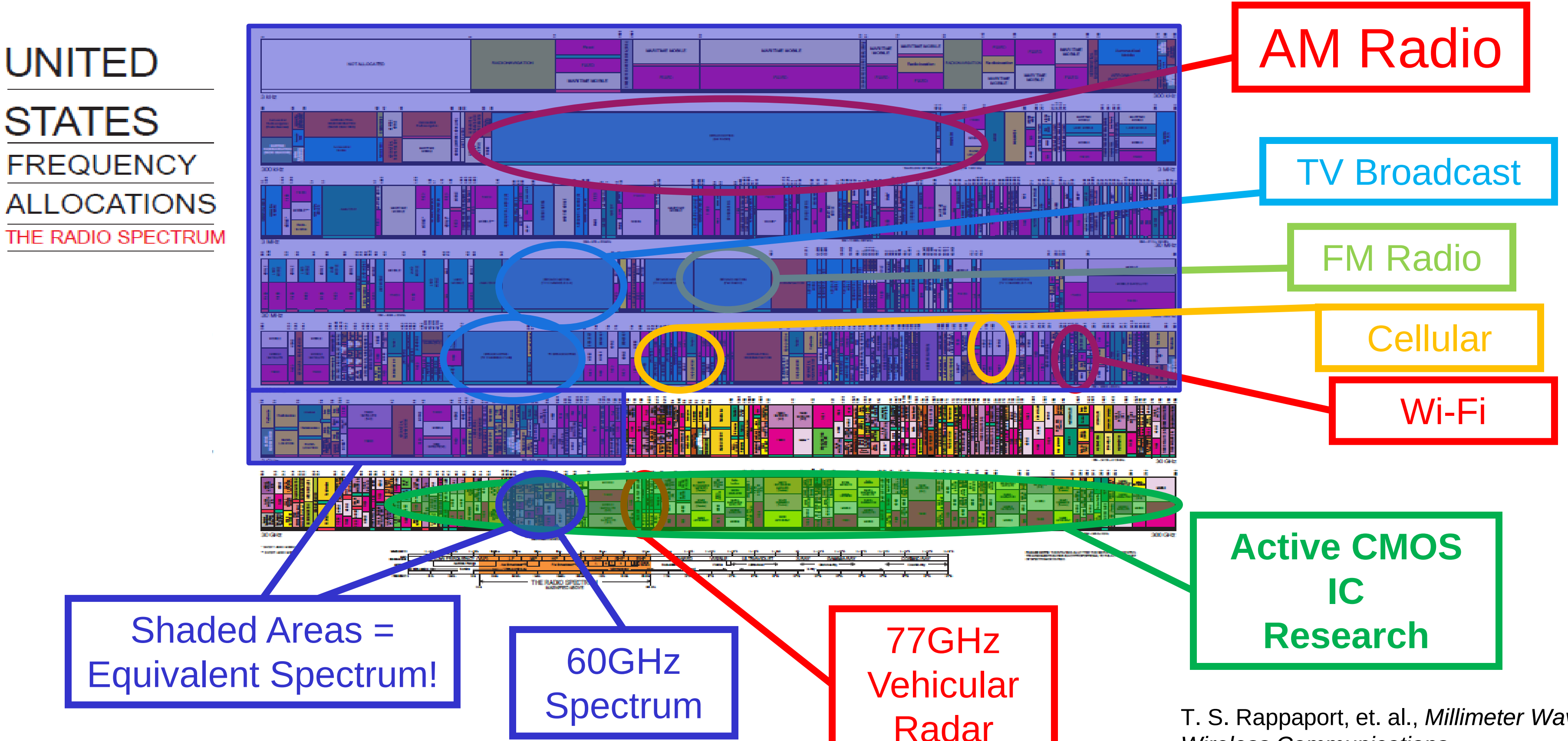
Phantom Cell concept can easily exploit higher freq. bands!

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 .

Spectrum = real estate



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

Spectrum Allocation History for 60GHz – Key mmWave Frequency Band

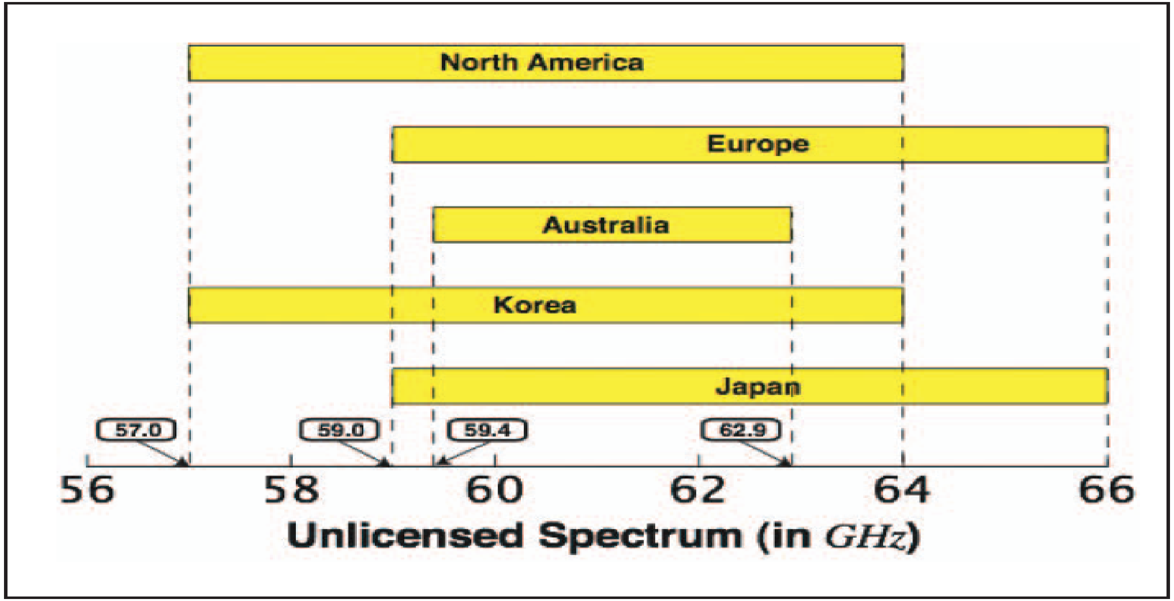
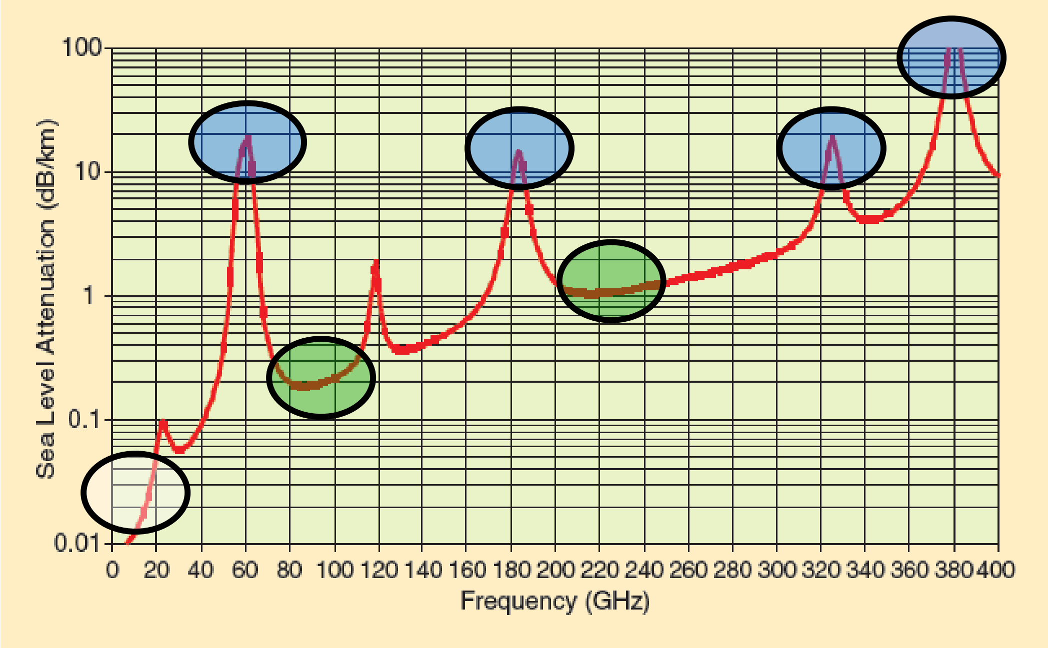


FIGURE 1 International unlicensed spectrum around 60 GHz.

- 60 GHz Spectrum allocation is worldwide
- 5 GHz common bandwidth among several countries

•Park, C., Rappaport, T.S. , "Short Range Wireless Communications for Next Generation Networks: UWB, 60 GHz Millimeter-Wave PAN, and ZigBee," Vol.14, No. 4, IEEE Wireless Communications Magazine, Aug. 2007, pp 70-78.
•G. L. Baldwin, "Background on Development of 60 GHz for Commercial Use," SiBEAM, inc. white paper, May 2007,

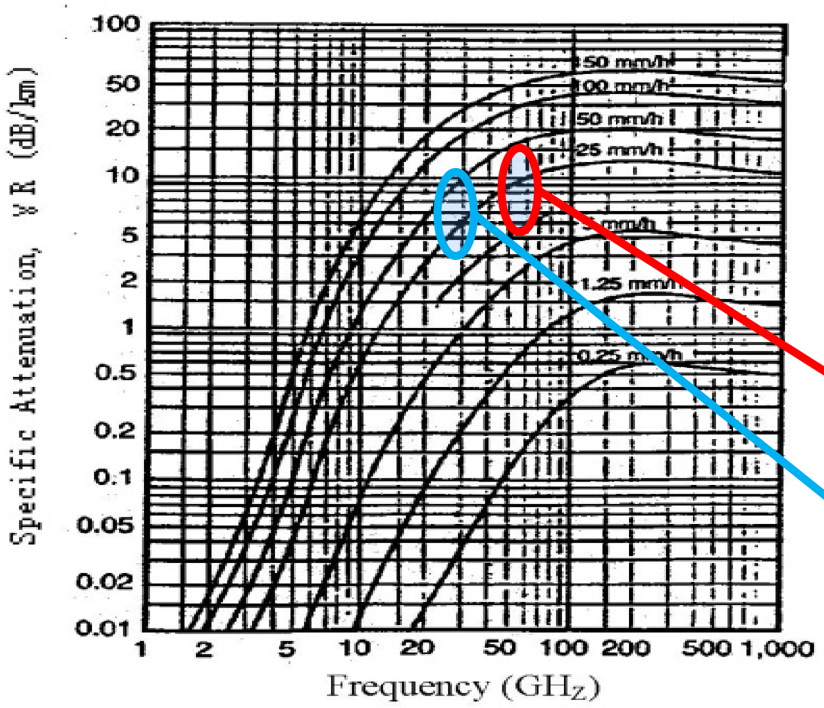
30 GHz and Above: Important Short and Long Range Applications



T.S. Rappaport, et. al, “State of the Art in 60 GHz Integrated Circuits and Systems for Wireless communications,” Proceedings of IEEE, August 2011, pp. 1390-1436.

- Additional path loss @ 60 GHz due to Atmospheric Oxygen
- Atmosphere attenuates: 20 dB per **kilometer**
- Many future sub-THz bands available for both cellular/outdoor and WPAN “whisper radio”

Rain Attenuation – No worries



Rain attenuation at 70 GHz band:

- Heavy rain (25mm/hr): 10 dB/km

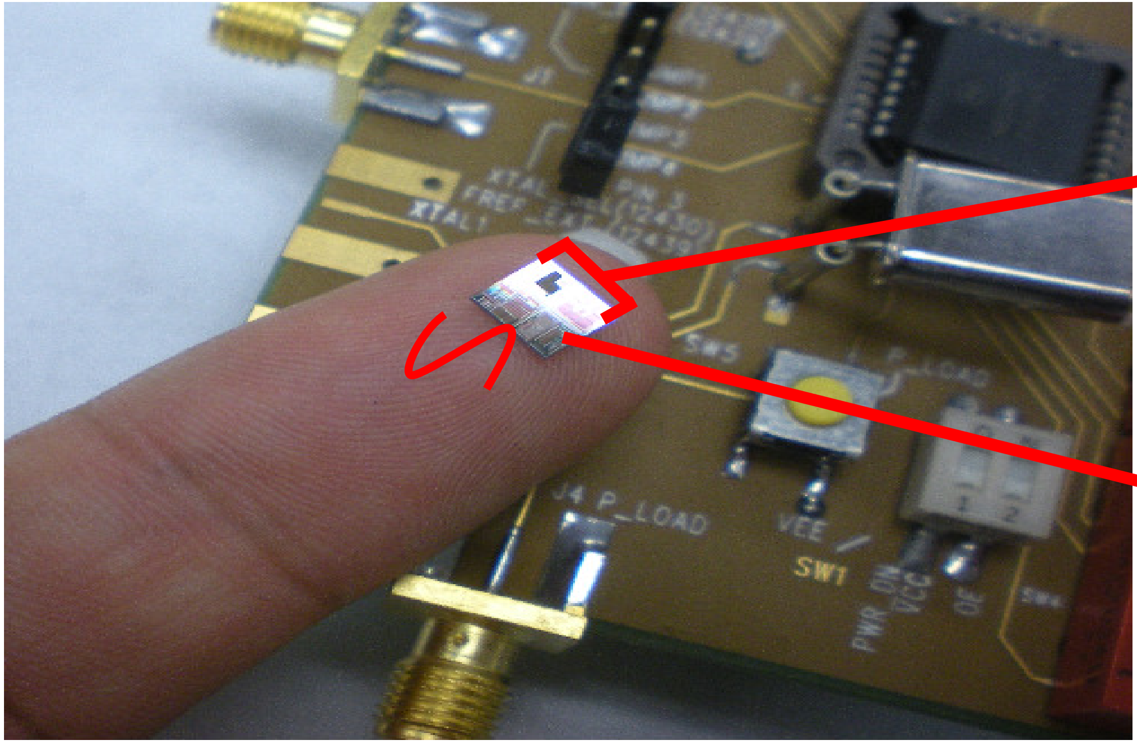
Cell size: 200 meters

Heavy Rainfall @ 73 GHz
2 dB attenuation @ 200m

Heavy Rainfall @ 28 GHz
1.2 dB attenuation @ 200m

Q. Zhao; J. Li; "Rain Attenuation in Millimeter Wave Ranges," International Symposium on Antennas, Propagation, & EM Theory, Oct 26-29, 2006.

mmWave Wavelength Visualization – 60GHz



5 millimeters
16 antennas

Integrated
Circuit

Early Work in Directional Channels

Overview of spatial channel models for antenna array communication systems
R.B. Ertel, et. al., IEEE PERSONAL COMMUNICATIONS, Vol. 5, No. 1, **February 1998**

Smart Antennas for Wireless Communications (book by Prentice-Hall)
J. C. Liberti, T.S. Rappaport, **c. 1999**

Application of narrow-beam antennas and fractional loading factor in cellular communication systems
Cardieri, et. al., IEEE TRANS. ON VEHICULAR TECHNOLOGY, Vol. 50, No. 3, **March 2001**

Spatial and temporal characteristics of 60-GHz indoor channels
Xu, et. al., IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL.. 20, NO. 3, **April 2002**

Wideband Measurement of Angle and Delay Dispersion for Outdoor/Indoor/ Peer-to-Peer Channels @ 1920 MHz
Durgin, et. al., IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 5, **May 2003**

1) **Multipath Shape Factor Theory** found new parameters to describe directional channels

2) RMS delay spreads, interference, and Doppler effects all shrink dramatically for small cell **directional antennas**
.
3) **Multipath power is arriving from several discrete directions in azimuth** instead of across a smooth continuum of azimuthal angles in NLOS channels.

Key Challenge: Range

- Friis' Law: $\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$
  - Free-space channel gain $\propto \lambda^2$, but antenna gains $\propto 1/\lambda^2$
  - For fixed physical size antennas in free space, frequency does not matter!
  - Path loss can be overcome with beamforming, independent of frequency!

- Shadowing: Significant transmission losses possible:
  - Brick, concrete > 35 dB
  - Human body: Up to 35 dB
  - But channel is rich in scattering and reflection, even from people

- It works! NLOS propagation uses reflections and scattering

Rappaport, et. al, "Millimeter wave mobile communications for 5G cellular: It will work!" IEEE Access, 2013

Cellular and Wireless Backhaul

Trends:

- Higher data usage
- Increase in base station density (femto/pico cells)
- Greater frequency reuse

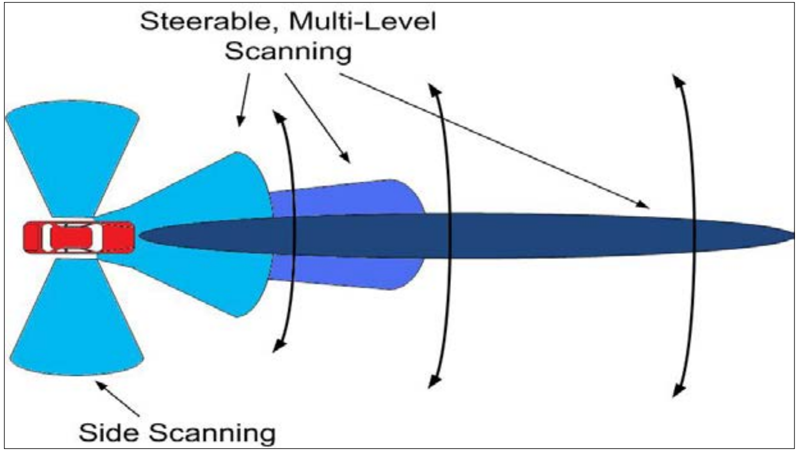
Problem: fiber optic backhaul is expensive and difficult to install.

Solution: Cheap CMOS-based wireless backhaul with beam steering capability.

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

Mobile & Vehicle Connectivity

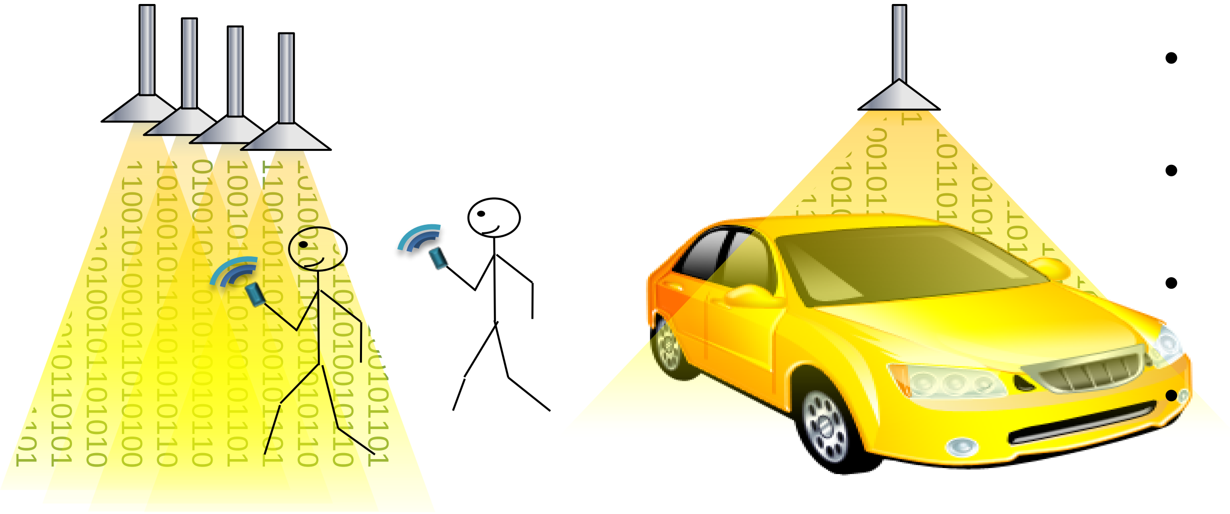
- Massive data rates
  - Mobile-to-mobile communication
  - Establish ad-hoc networks
- High directionality in sensing
  - Vehicular Radar and collision avoidance
  - Vehicle components connected wirelessly



T. S. Rappaport, et. al., *Millimeter Wave Wireless Communications,* Pearson / Prentice Hall, 2014

Future Applications

Information Showers

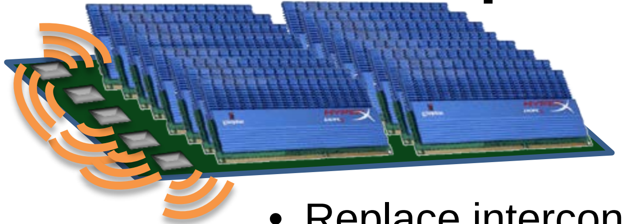


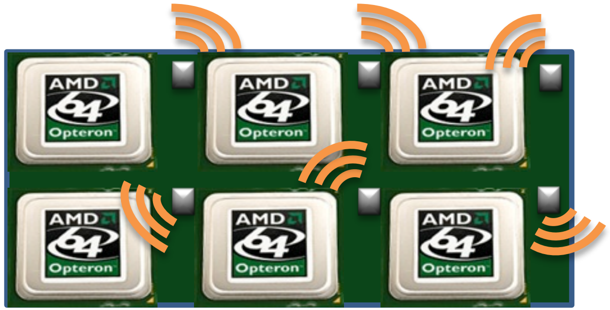
- The future: Showering of information
- Mounted on ceilings, walls, doorways, roadside
- Massive data streaming while walking or driving
- Roadside markers can provide safety information, navigation, or even advertisements

Gutierrez, F.; Rappaport, T.S.; Murdock, J. " Millimeter-wave CMOS On-Chip Antennas for Vehicular Electronic Applications," *72nd IEEE Vehicular Technology Conference Fall 2010.*

Future Applications

Decentralized Computing





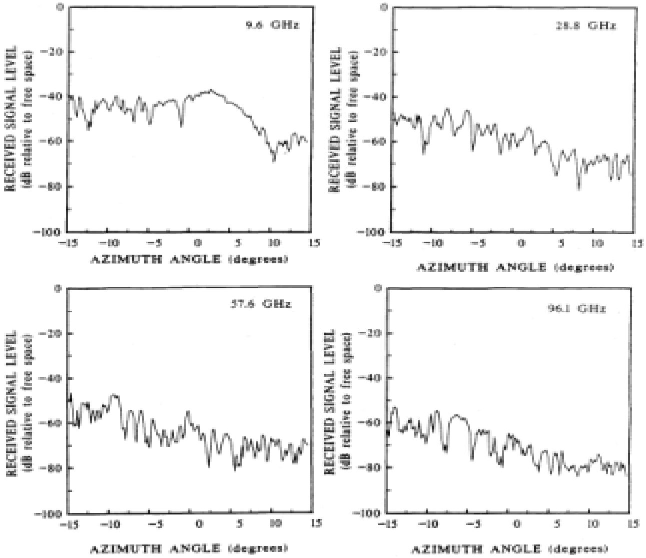
- Replace interconnect with wireless
- Applications in warehouse data centers
- Cooling servers is paramount problem
- Decentralize and focus cooling on heat-intensive components
- Increase efficiency

Keynote Address “The Emerging World of Massively Broadband Devices: 60 GHz and Above,” T. S. Rappaport, Wireless at Virginia Tech Symposium, Blacksburg Virginia, June 3-5, 2009.

Cellular Spectrum above 6 GHz
Will it happen, and will it work?
A look at past research

Past Research – Foliage Shadowing

- Attenuation due to foliage increases at mmWave frequencies.
- However, the spatial variation in shadowing is greater than lower frequencies.
- mmWave frequencies have very small wavelengths, hence smaller Frensel zone
- Wind may modify link quality



Above figure from: D.L. Jones, R.H. Espeland, and E.J. Violette, "Vegetation Loss Measurements at 9.6, 28.8, 57.6, and 96.1 GHz Through a Conifer Orchard in Washington State," U.S. Department of Commerce, NTIA Report 89-251, 1989.

Past Research – LMDS Coverage

Table 1. Percentage of locations where sufficient signal strength was NOT received for different antenna heights and ranges of distances from the transmitter.

Antenna Height	All Measurement Locations	< 3 km From Transmitter	<2 km From Transmitter	<1 km From Transmitter
11.3 m	32%	32%	28%	14%
7.3 m	54%	55%	50%	29%
3.4, 4.0 m	74%	73%	70%	52%

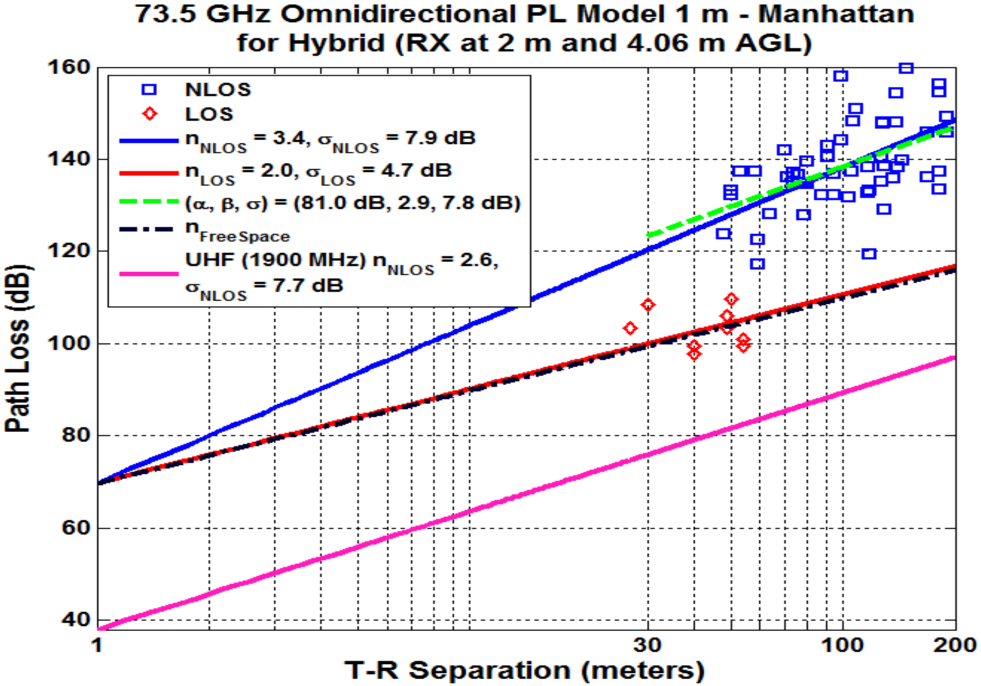
S.Y. Seidel and H.W. Arnold, "Propagation measurements at 28 GHz to investigate the performance of local multipoint distribution service (LMDS)," in IEEE Global Telecommunications Conference (Globecom), Nov. 1995, pp. 754-757.

- Seidel measured signal strength up to 5 km for wireless backhaul at 28 GHz
- Coverage area increases with receiver antenna height
- Receiver antenna scanned only in azimuth direction
- Our study showed *elevation* angle scanning increases coverage significantly

Channel Path Loss

- Path loss (PL) is important: SNR (coverage) and CIR (interference) – determines cell size

- Log-normal shadowing model is most commonly used



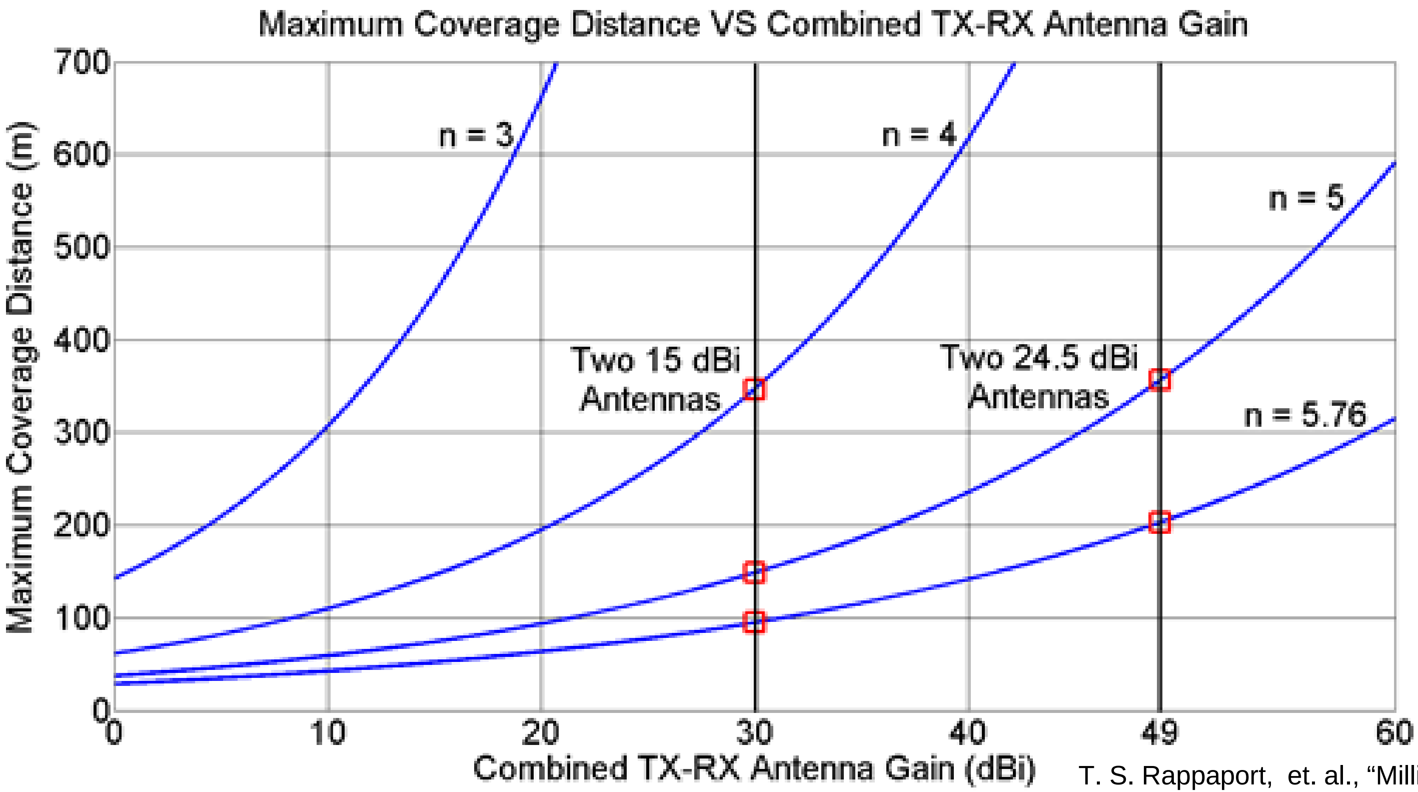
PL_0 is path loss measured at close-in distance d_0

Shadowing is log-Gaussian with standard deviation σ in dB about distant-dependent mean PL

T. S. Rappaport, Wireless Communications: Principles and Practice, 2nd Edition. New Jersey: Prentice-Hall, 2002.

G. R. MacCartney, M. K. Samimi, and T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz," IEEE 2014 Personal Indoor and Mobile Radio Communications (PIMRC), Sept. 2014, Washington, DC

Propagation Path Loss Exponent (PLE)



T. S. Rappaport, et. al., “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!” IEEE Access, vol.1, pp.335-349, 2013.

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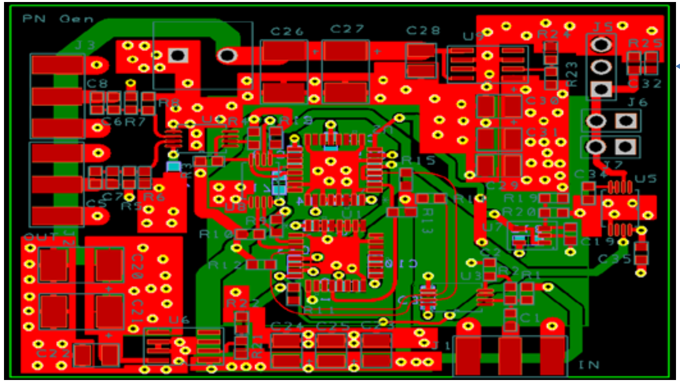
The World's first radio channel measurements for 5G cellular

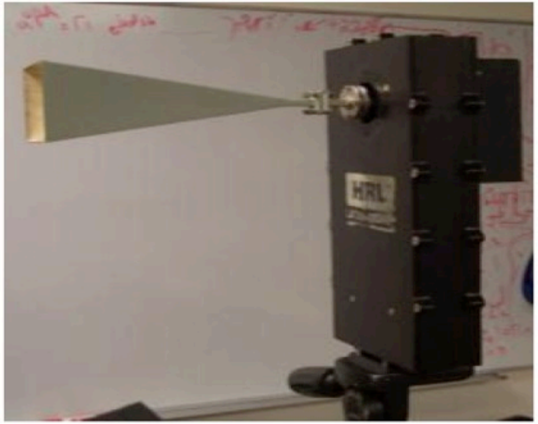
P2P (D2D), cellular, indoor
28, 38, 60, 73 GHz
In Texas and New York City

Sliding Correlator Hardware



Pseudorandom Noise (PN) Generator

- Chip Rate up to 830MHz
- Size 2” X 2.6”
- 11 bit Sequence
- Custom design



Upconverter and Downconverter assemblies at 38 and 60 GHz, newer ones built at 28 GHz, 72 GHz

Sliding Correlator Hardware

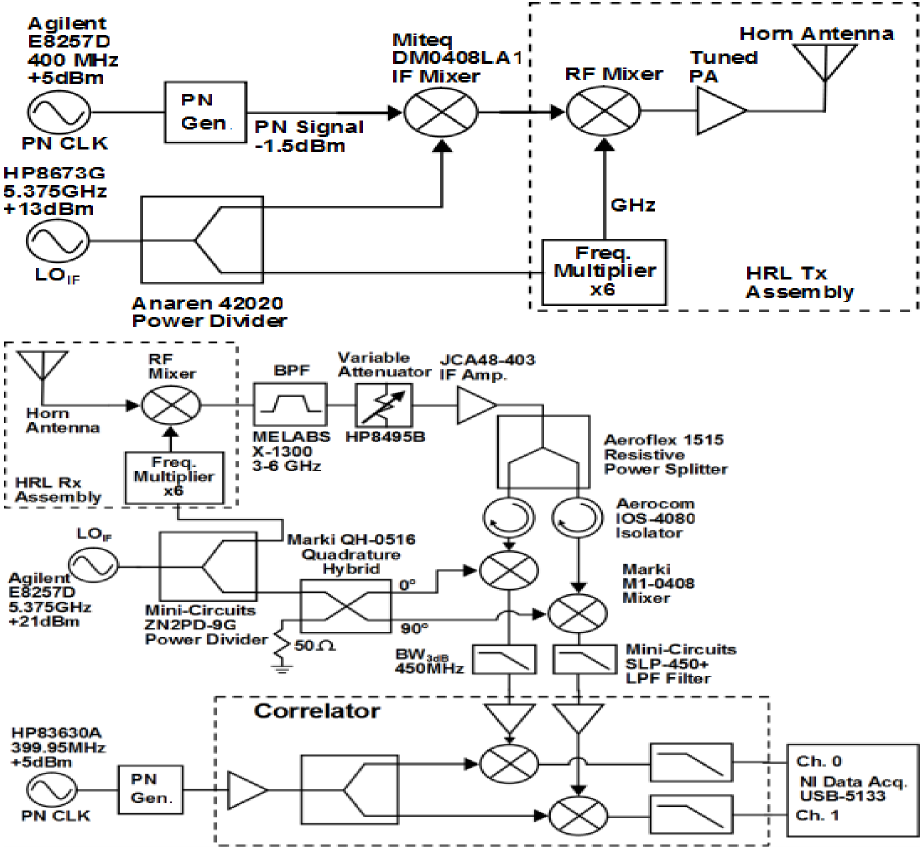
Transmitter

- PN sequence Generator PCB
- IF frequency of 5.4 GHz
- Changeable RF upconverter for 28, 38 , 60 , 72 GHz

Receiver

- Changeable RF downconverter
- IQ demodulation from IF to baseband using quadrature hybrid LO phase shifting

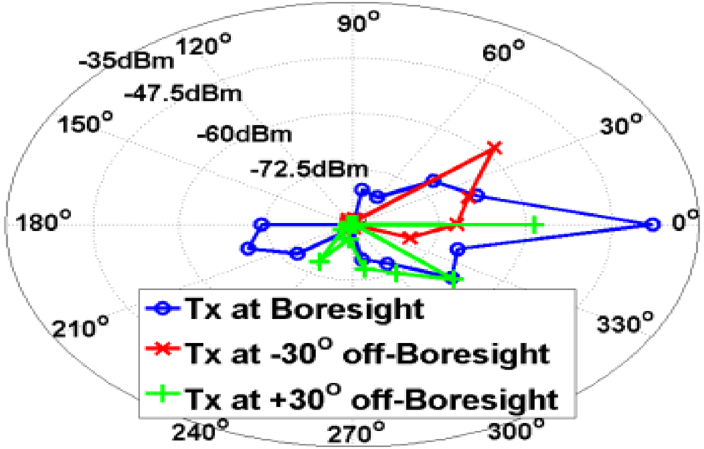
- Correlation circuit for multiplying and filtering PN signals
- Data Acquisition using NI USB-5133 with LabVIEW control



2011 Measurements at University of Texas

- Peer-to-Peer 38 and 60 GHz
  - Antennas 1.5m above ground
  - Ten RX locations (18-126m TR separation)
  - Both LOS and NLOS links measured using 8º BW 25dBi gain antennas
- Cellular (rooftop-to-ground) at 38 GHz
  - Four TX locations at various heights (8-36m above ground) with TR separation of 29 to 930m.
  - 8º BW TX antenna and 8º or 49º(13.3dBi gain) RX antenna. ~half of locations measured with 49º ant.
  - LOS, partially-obstructed LOS, and NLOS links
  - Outage Study – likelihood of outage
    - Two TX locations of 18 and 36m height.
    - 8º BW antennas
    - 53 random RX locations

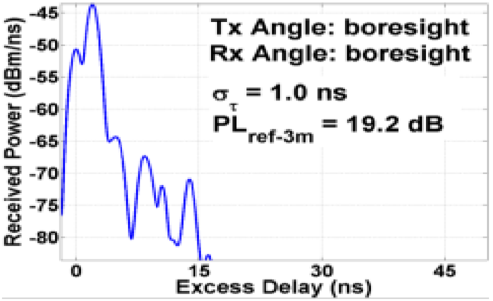
60 GHz AOA P2P (D2D) Measurements

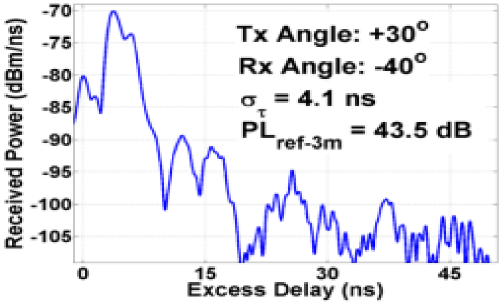


- **Observation**: Links exist at only few angles

- Thus, full AOA is not needed to characterize channel

- Only angles that have a signal are measured





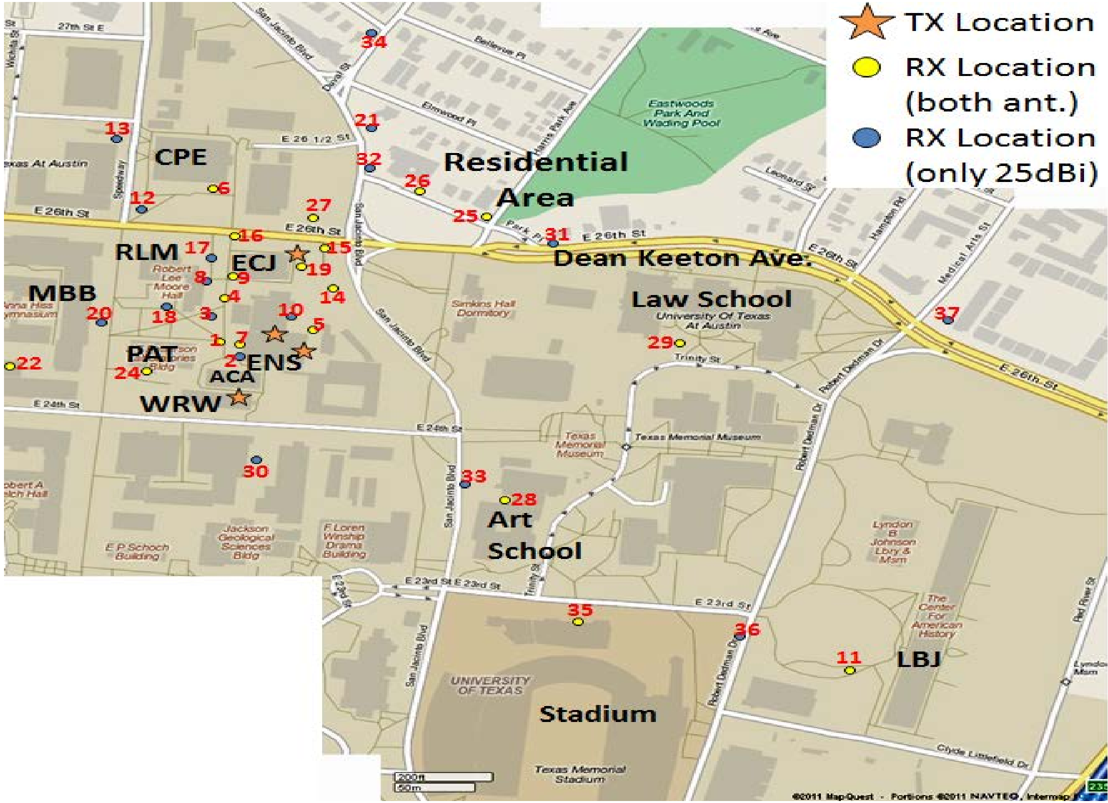
Ben-Dor, E.; Rappaport, T.S.; Yijun Qiao; Lauffenburger, S.J., "Millimeter-Wave 60 GHz Outdoor and Vehicle AOA Propagation Measurements Using a Broadband Channel Sounder," *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE* , vol., no., pp.1,6, 5-9 Dec. 2011

Cellular Measurement Map

Transmitter Locations

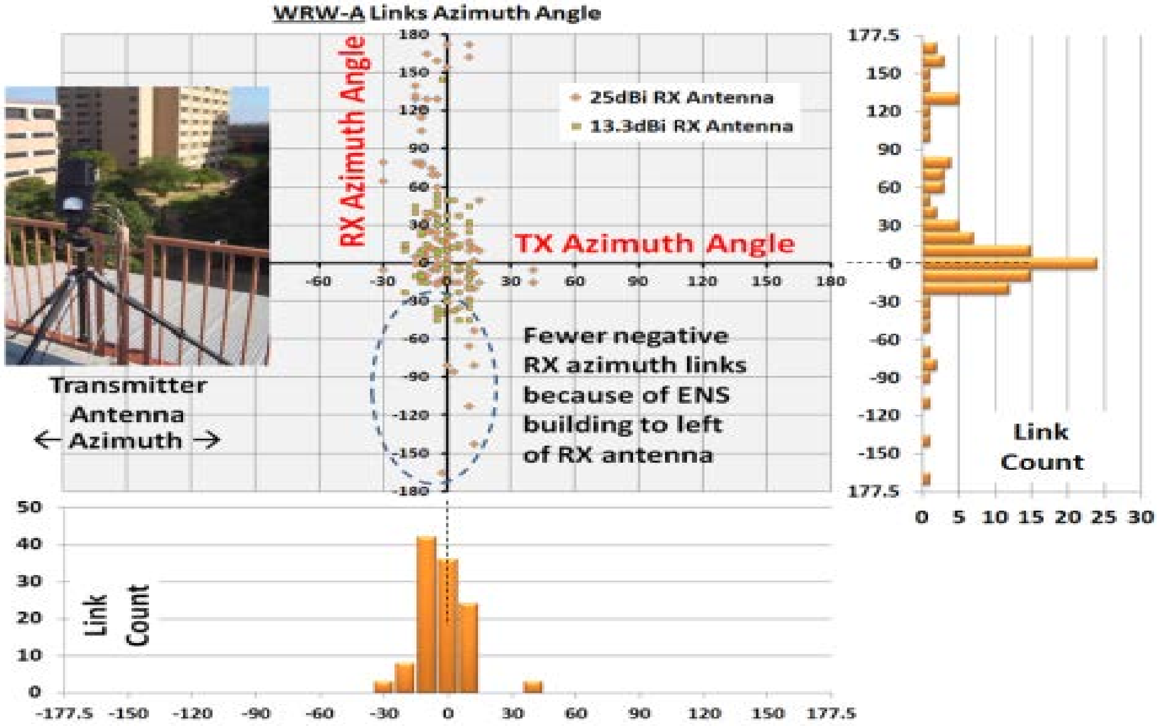
WRW-A ENS-A

ECJ ENS-B



38 GHz Cellular AOA

TX height 23m above ground

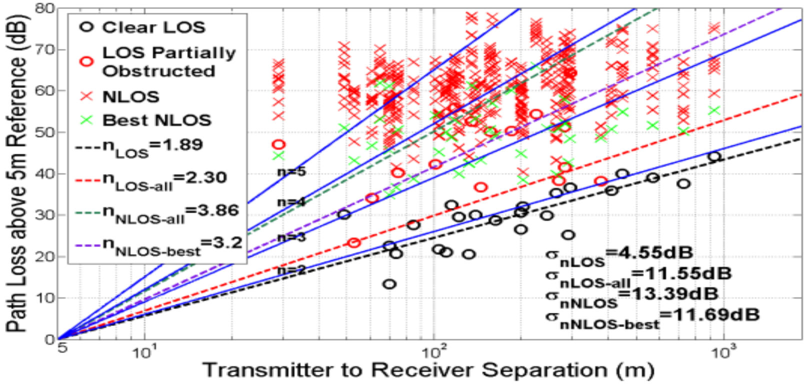


Histogram of RX angles for all links made using 25dBi antennas (10^{o} bins)

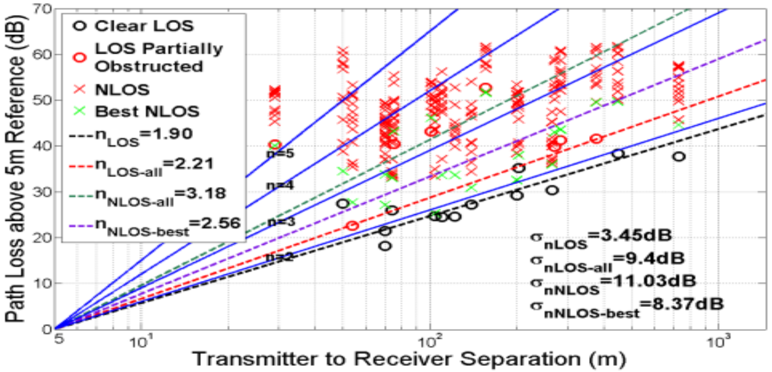
Histogram of TX angles for all links made using 25dBi antennas (10^{o} bins)

38 GHz Cellular Path Loss

38 GHz Path Loss, 25dBi RX Antenna



38GHz Path Loss, 13.3dBi RX Antenna



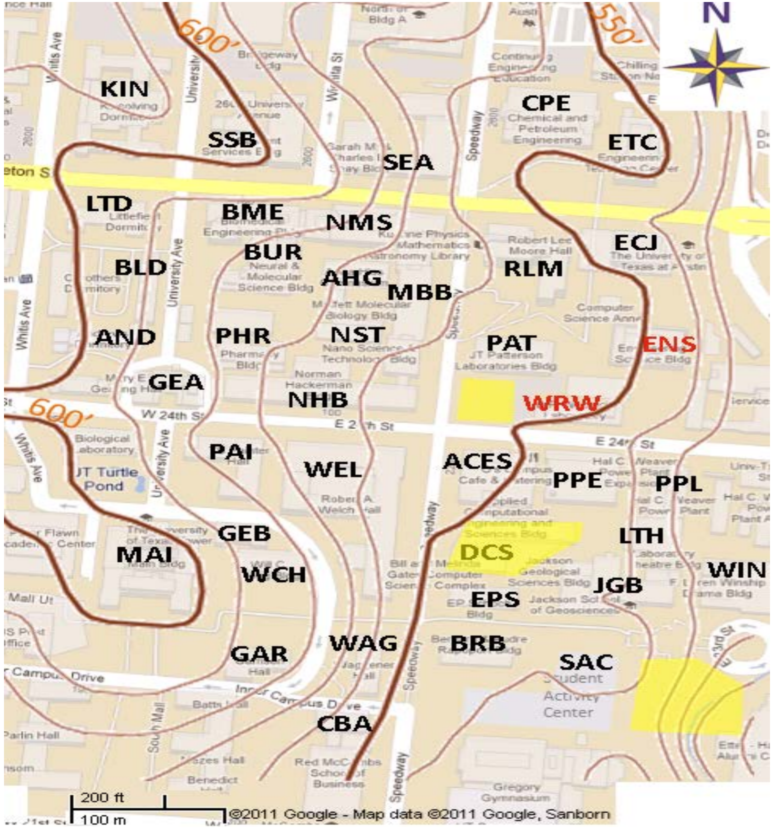
- Measurements performed using 13.3 and 25dBi horn antennas
- Similar propagation was seen for clear LOS links (n = 1.9)
- Wider beam antenna captured more scattered paths in the case of obstructed LOS
- Large variation in NLOS links

	25dBi RX Ant.		13.3dBi RX Ant.	
	LOS	NLOS	LOS	NLOS
Path Loss Exponent	2.30 (clear 1.90)	3.86 (best: 3.20)	2.21 (clear 1.89)	3.18 (best: 2.56)
Path Loss std. dev. (dB)	11.6 (clear 4.6)	13.4 (best 11.7)	9.4 (clear 3.5)	11.0 (best 8.4)

Rappaport, T.S.; Gutierrez, F.; Ben-Dor, E.; Murdock, J.N.; Yijun Qiao; Tamir, J.I., "Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications," *Antennas and Propagation, IEEE Transactions on* , vol.61, no.4, pp.1850,1859, April 2013

38 GHz Outage Study

- 2 adjacent TX locations
  - ENS: Western side of an **8-story** building (36 m high)
  - WRW: Western side of a **4-story** building (18 m high)
- 53 randomly selected outdoor RX locations (indoor excluded)
- 460x740 meter region examined
- Contour lines on map show a 55 feet elevation increase from the TX locations to the edge of the investigated area



Rappaport, T.S.; Gutierrez, F.; Ben-Dor, E.; Murdock, J.N.; Yijun Qiao; Tamir, J.I., "Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications," *Antennas and Propagation, IEEE Transactions on* , vol.61, no.4, pp.1850,1859, April 2013

38 GHz Outage TX Location Comparison

Transmitter Location	Height	% Outage with >160 dB PL	% Outage with >150 dB PL
TX 1 ENS	36 m	18.9% all, 0% < 200 m	52.8% all, 27.3 % < 200 m
TX 2 WRW	18 m	39.6% all, 0% < 200 m	52.8% all, 10% < 200 m

Similarities:

- No outages within 200 m were observed.
- Outage location clustering.

Differences:

- The lower (WRW) TX location achieved better coverage for a short range.
- The higher (ENS) TX location produced links at obstructed locations over 400 m away.
- Shorter WRW cellsite results in a tighter cell (i.e. less interference), yet its range is significantly smaller in distance.

Rappaport, T.S.; Gutierrez, F.; Ben-Dor, E.; Murdock, J.N.; Yijun Qiao; Tamir, J.I., "Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications," *Antennas and Propagation, IEEE Transactions on* , vol.61, no.4, pp.1850,1859, April 2013

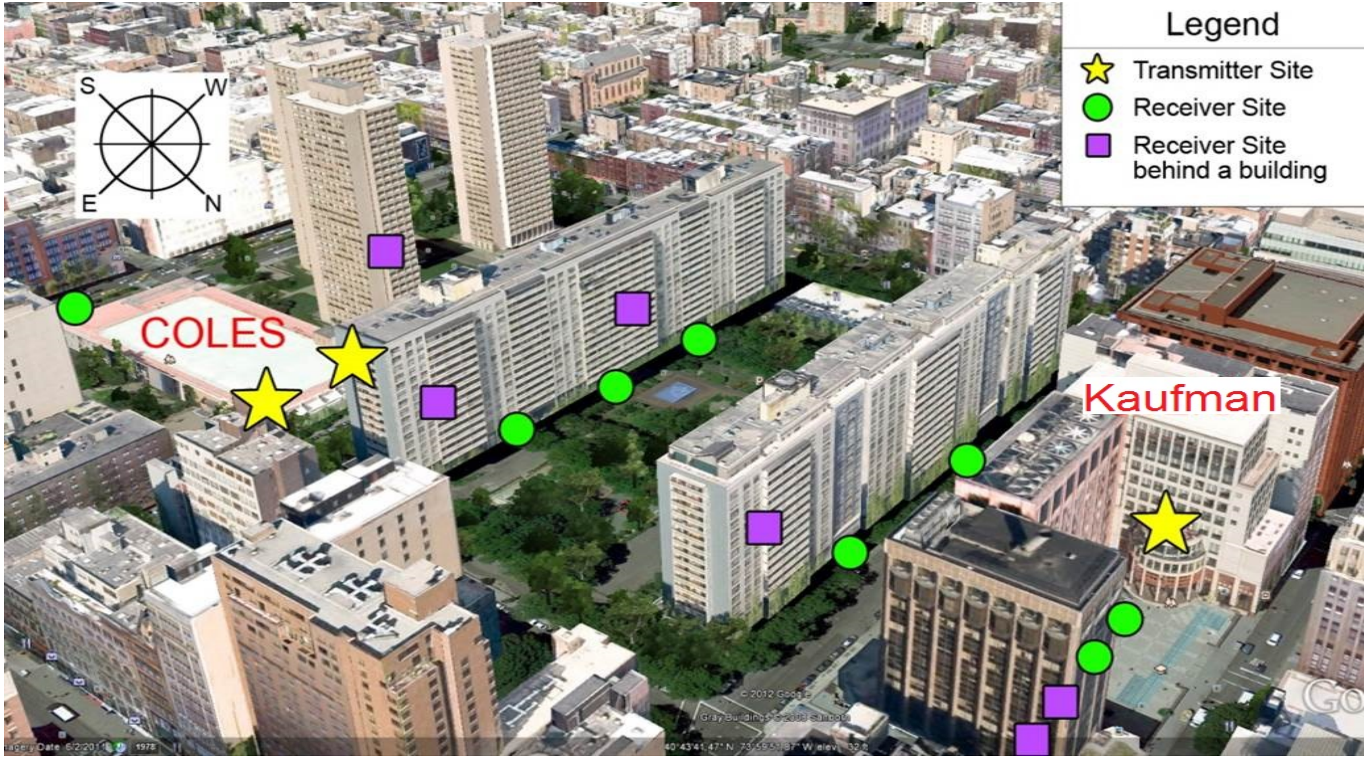
28 GHz Measurements in 2012 Dense Urban NYC

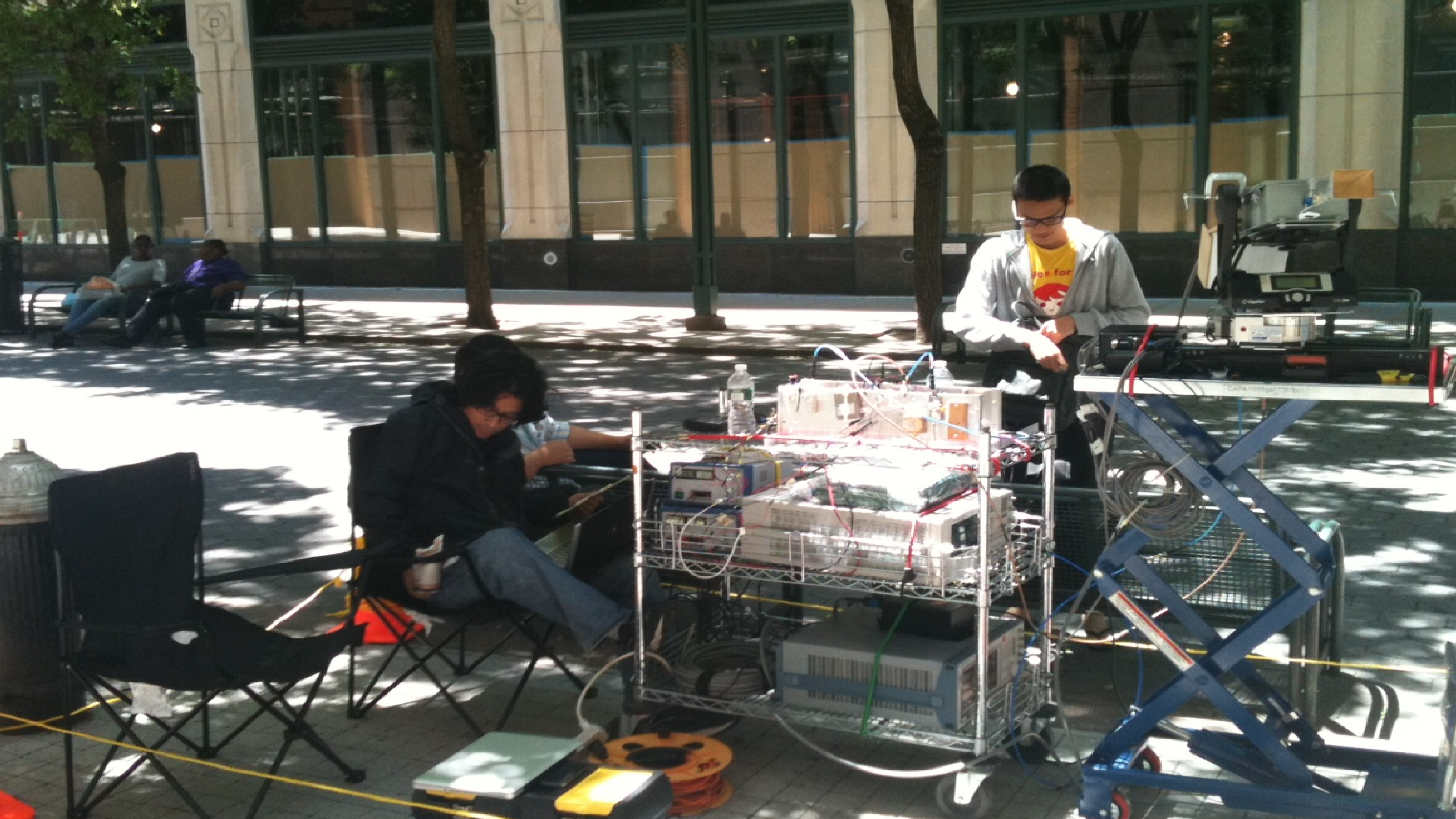
- 4 TX sites
- 33 RX sites (35 w/ LOS)

- 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






Hilfiger


NYU
WIRELESS
NYU


NYU
100

NYU POLYTECHNIC SCHOOL OF ENGINEERING

28 GHz Channel Sounder 2012

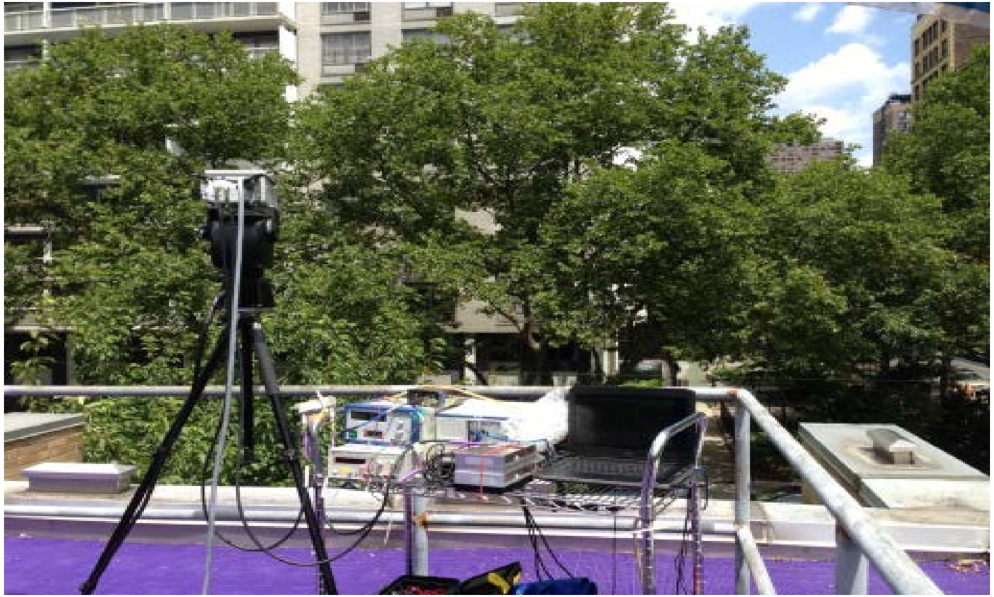
NYU WIRELESS

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.

73 GHz Channel Sounder 2013


TX Hardware


RX Hardware

Summary of Measurement Locations in NYC

28 GHz Campaign in Manhattan for 200 m cell (2012)

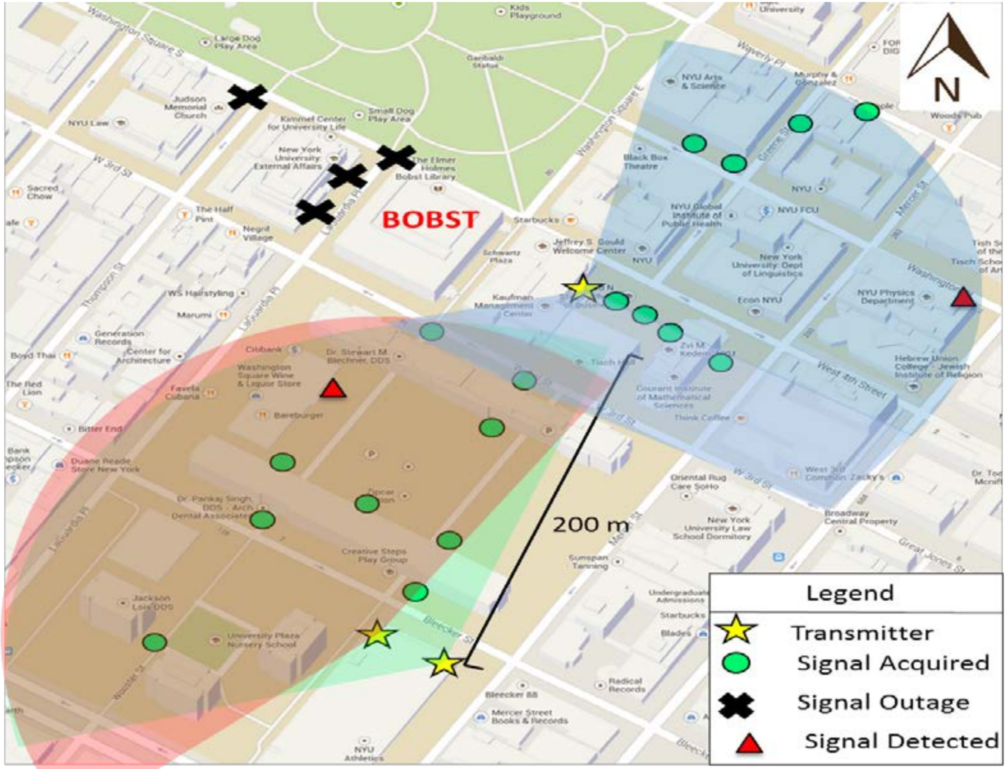
TX Location	TX Height (meters)	Number of RX Locations	RX Height (meters)
COL1	7	10	1.5
COL2	7	10	
KAU	17	15	

73 GHz Campaign in Manhattan for 200 m cell (2013)

TX Location	TX Height (meters)	Number of RX Locations (Cellular)	RX Height (Cellular) (meters)	Number of RX Locations (Backhaul)	RX Height (backhaul) (meters)
COL1	7	11	2	7	4.06
COL2	7	9		14	
KAU	17	11		11	
KIM1	7	3		3	
KIM2	7	2		3	

Signal Outage at 28 GHz in NYC for Using all Unique Pointing Angles at Each Site

- 75 TX-RX separation distances range from 19 m to 425 m
- Signal acquired up to 200 m TX-RX separation
- 14% of 35 TX-RX location combinations within 200 m are found to be outage
- For outage, path loss > 178 dB (5 dB SNR per multipath sample) for all unique pointing angles

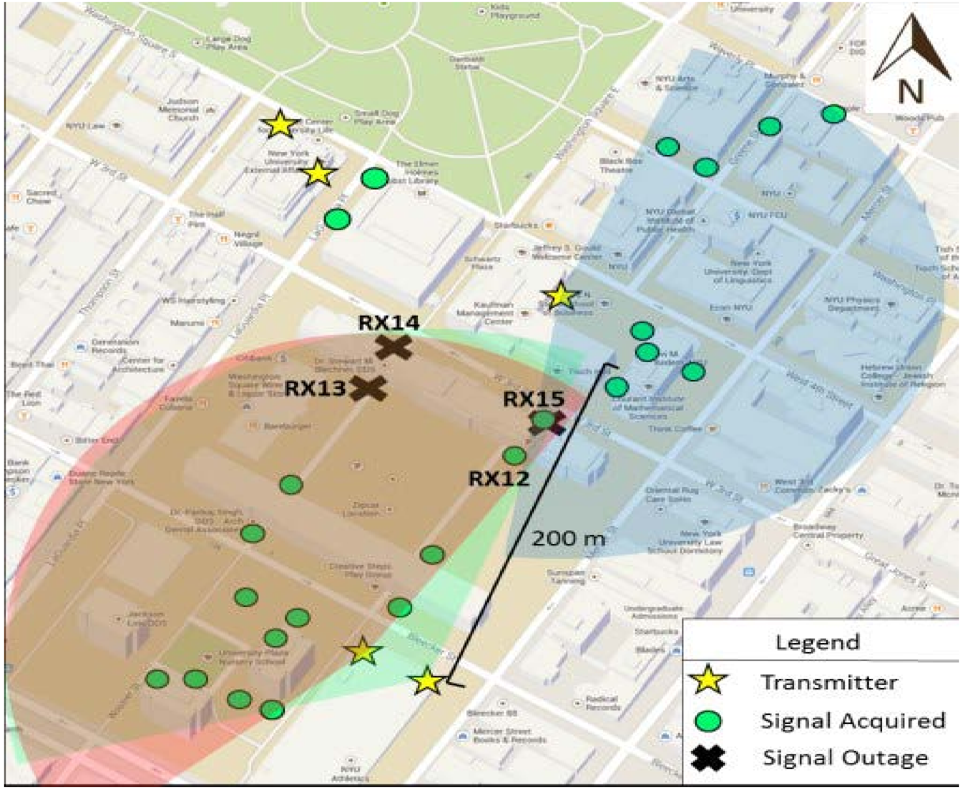


-S. Nui, G. MacCartney, S. Sun, T. S. Rappaport, “28 GHz and 73 GHz Signal Outage Study for Millimeter Wave Cellular and Backhaul Communications,” 2014 IEEE Int. Conf. on Comm. (ICC), Sydney, Australia.

-T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!” IEEE Access, vol. 1, pp. 335–349, 2013.

Signal Outage at 73 GHz in NYC for All Unique Pointing Angles at Each Site

- 74 TX-RX separation distance range from 27 m to 216 m
- 17% of 36 TX-RX location combinations were outage in mobile scenario; 16% of 38 TX-RX location combinations found to be outages in backhaul scenario
- For outage, path loss > 181 dB (5 dB SNR per multipath sample) for all unique pointing angles
- Receiver locations chosen based on previous 28 GHz campaign



* Only a limited amount of RX selected for KIM1 and KIM2

S. Nui, G. MacCartney, S. Sun, T. S. Rappaport, "28 GHz and 73 GHz Signal Outage Study for Millimeter Wave Cellular and Backhaul Communications," 2014 IEEE Int. Conf. on Comm. (ICC), Sydney, Australia.

Signal Outage (200 m Cell) in NYC using Adaptive Single Beam Antennas

Transmitter Locations	Transmitter Height (m)	Percentage of Outage for >Max. Measurable Path Loss		
		28 GHz	73 GHz	
		Cellular	Cellular	Backhaul
COL1	7	10%*	27%	42%
COL2	7	10%	33%	15%
KAU	17	20%*	0%	0%
KIM1	7	N/A	0%	0%
KIM2	7	N/A	0%	0%
Overall		14%	17%	16%

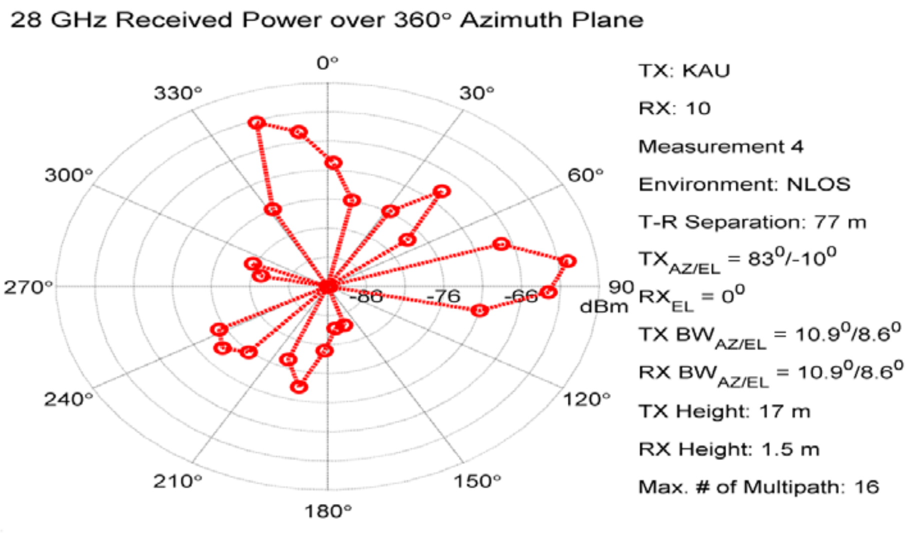
At 28 GHz in cellular measurements the estimated outage probability is 14% for all RX locations within 200 meters;

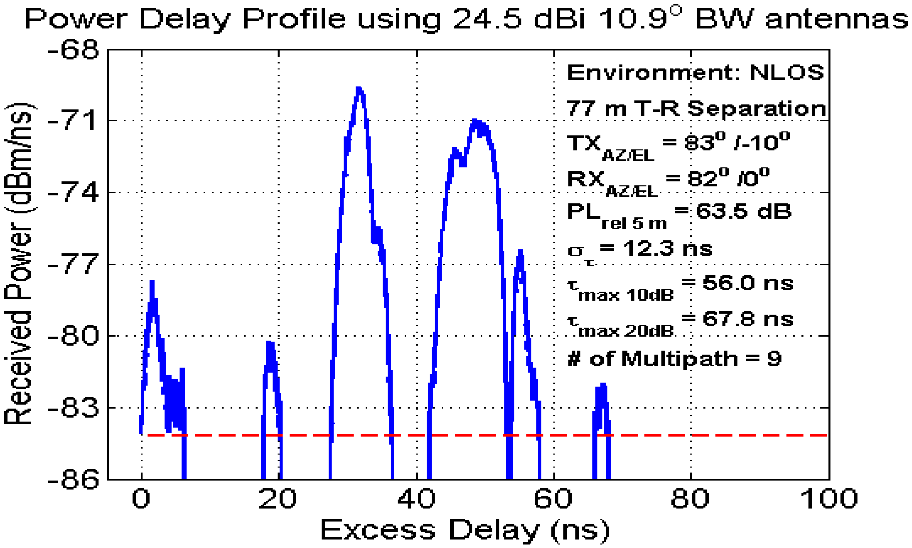
At 73 GHz the outage probabilities are 16% and 17% within 216 meters cell size for backhaul and cellular access scenarios, respectively;

Site-specific propagation planning easily predicts outage.

*Published ICC '14 paper erroneously stated 20% and 50% for distances up to 425 m– corrected here.

Typical Measured Polar Plot and PDP at 28 GHz or 73 GHz

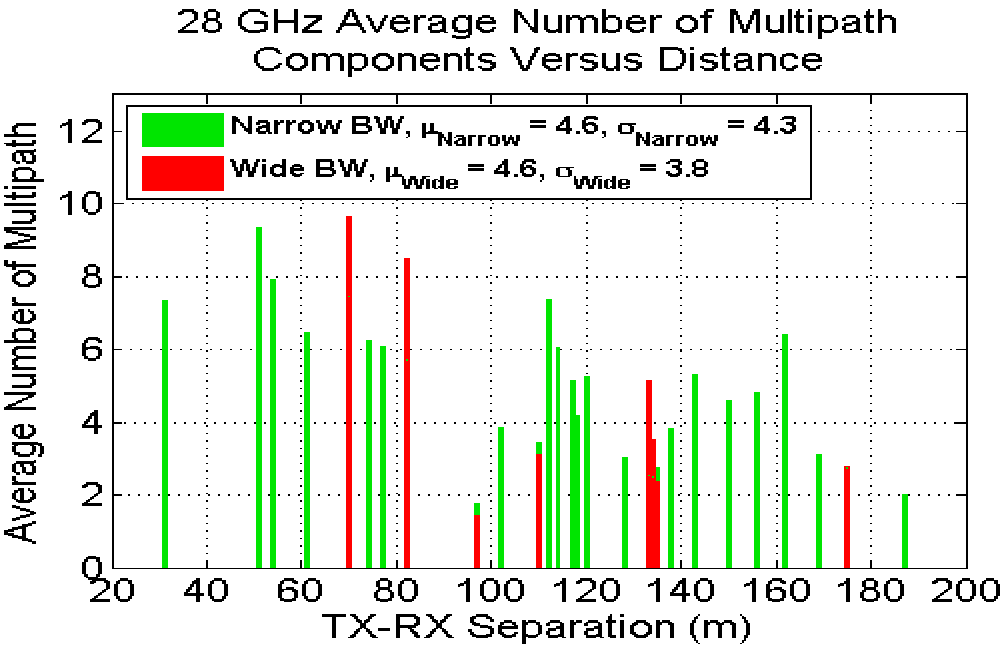




Signals were received at 23 out of 36 RX azimuth angles (10 degree increments)

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

No. of Multipath Components at 28 GHz for Unique Directional Angle Combinations



Average number of multipath components (MPCs) per distance:
First increases and then decreases with the increasing distance

Average number of MPCs per PDP:
Nearly identical for both the narrow-beam (10.9-degree HPBW) and wide-beam (28.8-degree HPBW) antenna measured cases

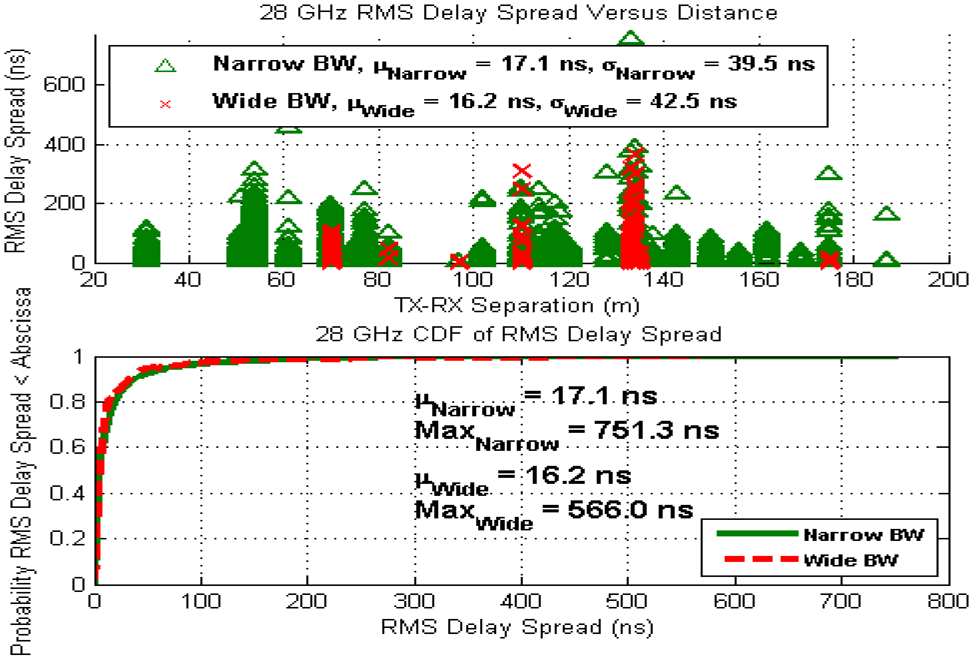
S. Sun, T. S. Rappaport, “Wideband mmWave Channels: Implications for Design and Implementation of Adaptive Beam Antennas ,” IEEE 2014 Intl. Microwave Symp. (IMS), June 2014, Tampa, Fl

RMS Delay Spread at 28 GHz

Measured RMS delay spread vs. T-R separation distance:
Smaller RMS delay spreads at larger distances (near 200 m) due to large path loss

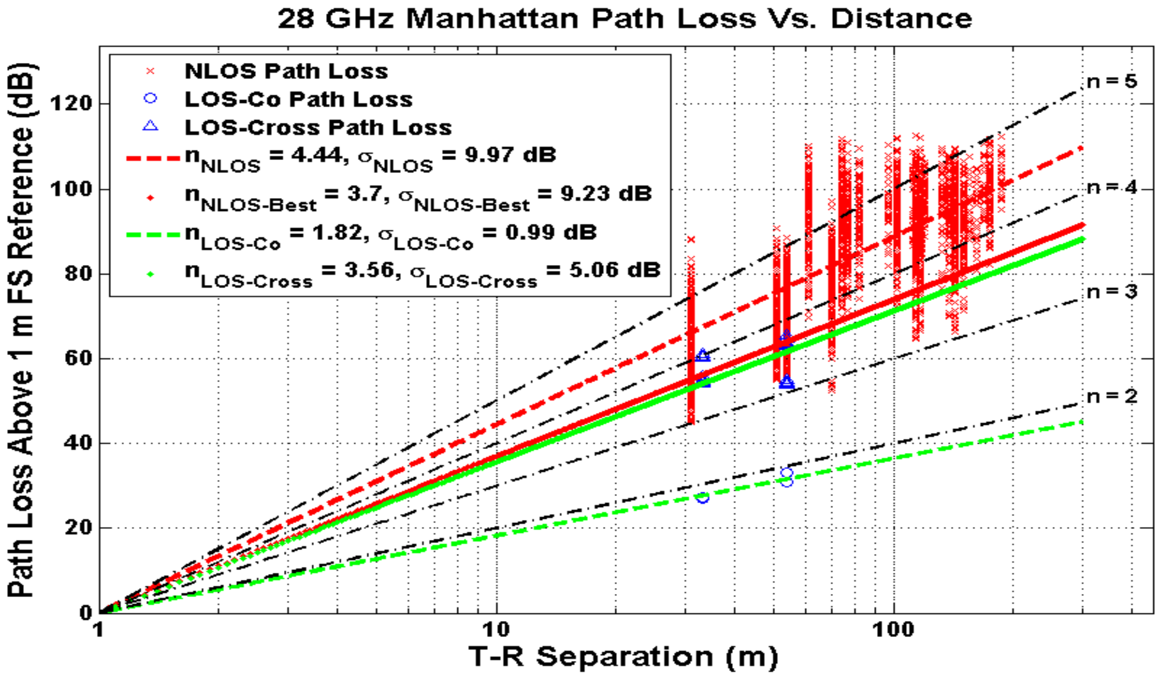
CDF of RMS delay spread:
Average and maximum RMS delay spreads are slightly smaller for wide-beam antenna case due to lower antenna gain thus smaller detectable path loss range

Average RMS delay spread values are only slightly larger than those for 38 GHz in suburban environments



Sun, S., Rappaport, T. S., "Wideband mmWave channels: Implications for design and implementation of adaptive beam antennas," 2014 IEEE International Microwave Symposium (IMS2014), Tampa, FL, June, 2014.

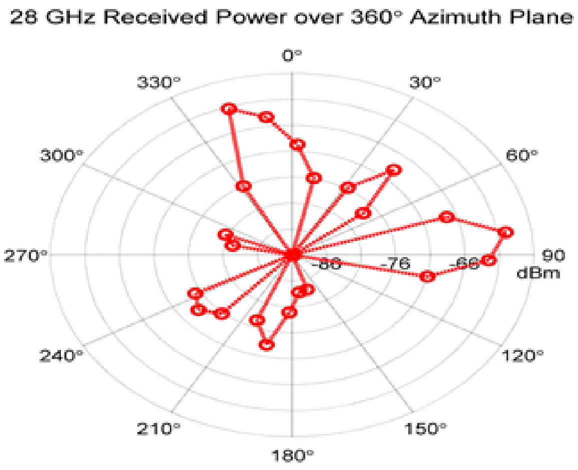
28 GHz Directional Path Loss Models



Each point on scatter plot represents a unique pointing angle for TX and RX horn antennas

T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, F. Gutierrez, “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!” IEEE Access, vol.1, pp.335-349, 2013.

Equal-Gain Combining for Different Pointing Angels at 28 GHz



	PLE	STD (dB)
Overall	4.47	10.20
One best beam	3.68	8.76
Two best beam (NC)	3.55	8.96
Two best beam (C)	3.41	9.03
Three best beam (NC)	3.49	9.12
Three best beam (C)	3.26	9.25
Four best beam (NC)	3.44	9.21
Four best beam (C)	3.15	9.39

S. Sun, T. S. Rappaport, “Wideband mmWave Channels: Implications for Design and Implementation of Adaptive Beam Antennas ,” IEEE 2014 Intl. Microwave Symp. (IMS), June 2014, Tampa Bay

RX (UE) Beam combining results using 1 m free space reference distance for the 7-m high TX antenna
“PLE” is path loss exponent, “STD” is shadowing std. dev., “NC” is noncoherent combining, “C” denotes coherent combining.

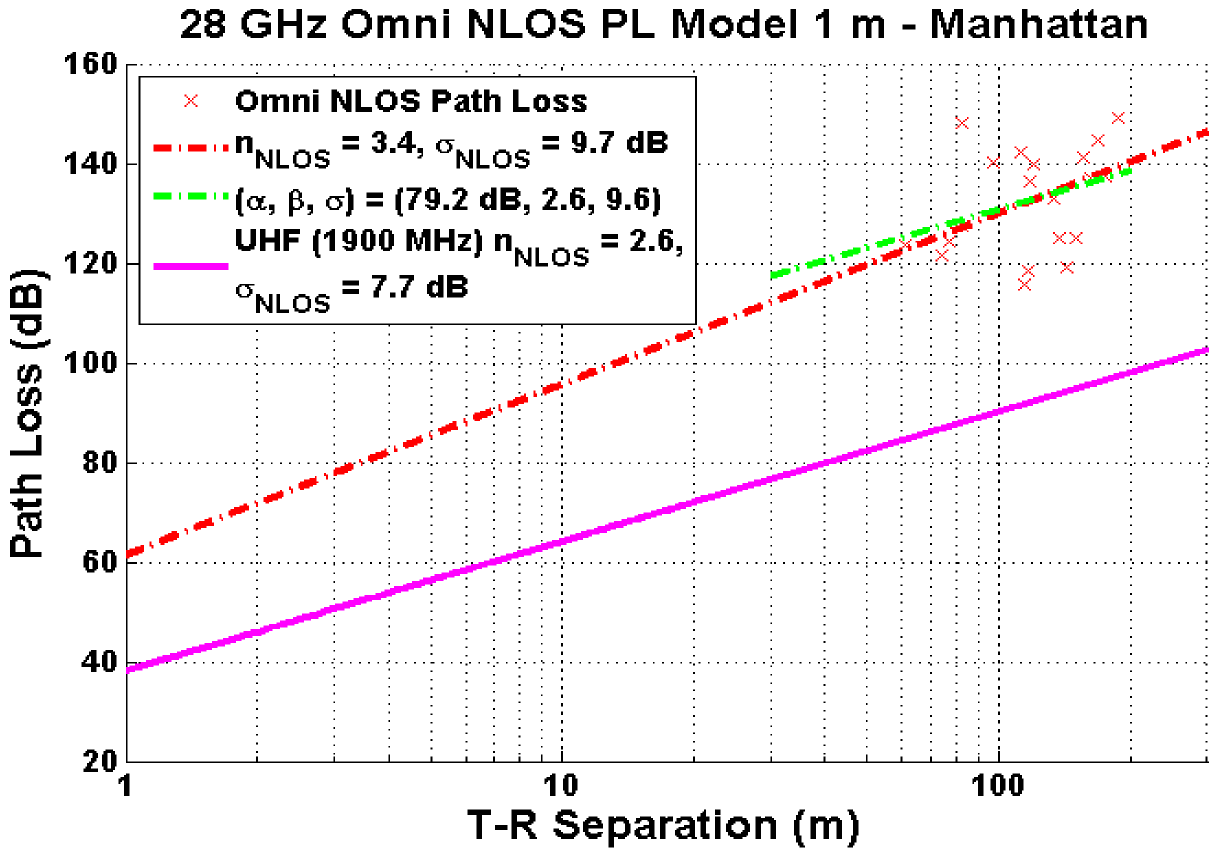
Coherent combining of 2 beams (n=3.41) < Noncoherent combining of 4 beams (n=3.44)

Coherent combining of 4 beams (n=3.15) < single best beam (n=3.68)

Path gain: 13.2 dB/decade in distance w/ 4 strongest beams coherently combined at different pointing angles compared to randomly pointed single beam.

Path gain: 5.3 dB/decade w/4 beams over single best beam (1.4X range increase)

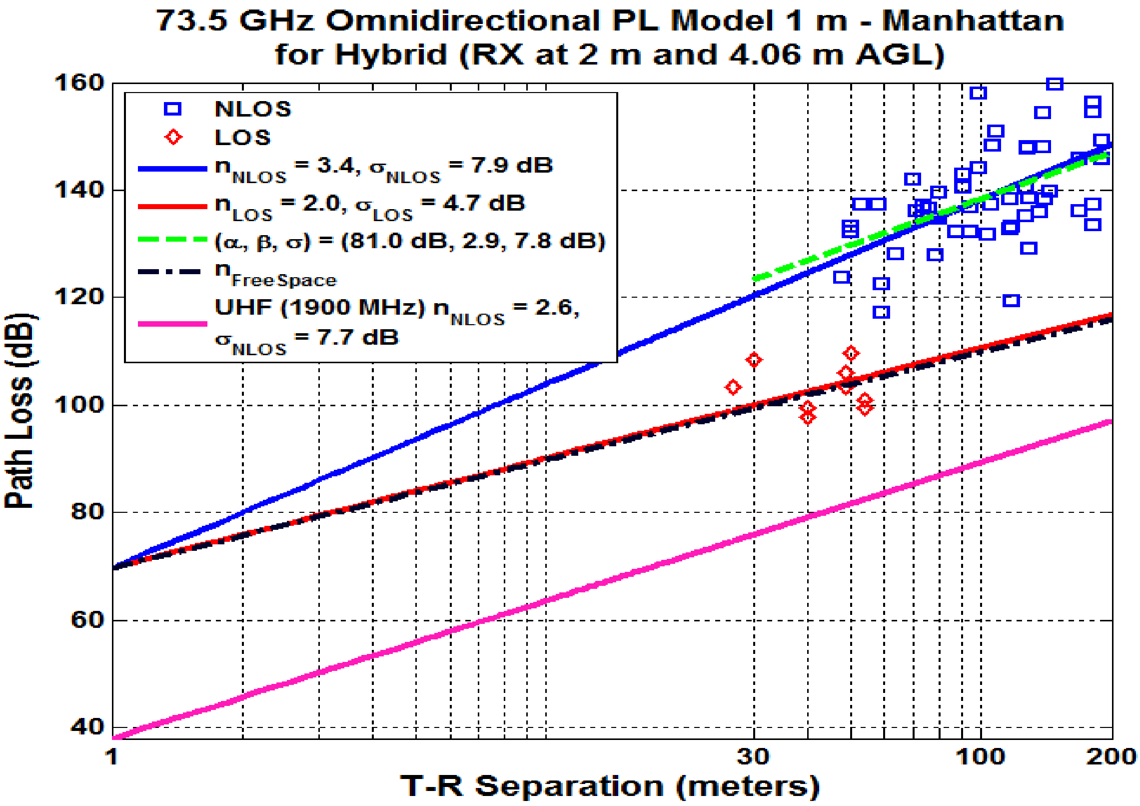
28 GHz NLOS Omnidirectional Path Loss Models



G. R. MacCartney, M. K. Samimi, and T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz," IEEE *2014 Personal Indoor and Mobile Radio Communications (PIMRC),* Sept. 2014, Washington, DC

K. Blackard, M. Feuerstein, T. Rappaport, S. Seidel, and H. Xia,"Path loss and delay spread models as functions of antenna height for microcellular system design," in *Vehicular Technology Conference, 1992, IEEE 42nd*, May 1992, pp. 333–337 vol.1.

73 GHz Omnidirectional Models for (Hybrid) Backhaul/Mobile RX Scenario



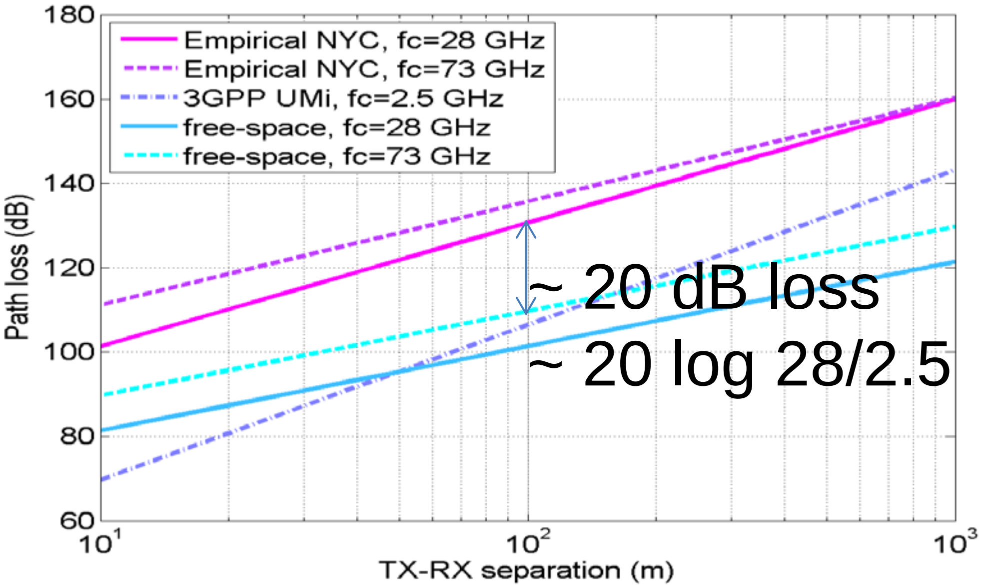
- Channel gain $\propto \lambda^2$, antenna gains $\propto 1/\lambda^2$
- Frequency does not matter!
- Path loss can be overcome with beamforming, independent of frequency!

S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges,” Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

K. Blackard, M. Feuerstein, T. Rappaport, S. Seidel, and H. Xia,“Path loss and delay spread models as functions of antenna height for microcellular system design,” in 1992 IEEE *Vehicular Technology Conference,* May 1992, pp. 333–337 vol.1.

G. R. MacCartney, M. K. Samimi, and T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz,“ IEEE 2014 Personal Indoor and Mobile Radio Communications (PIMRC), Sept. 2014, Washington, DC

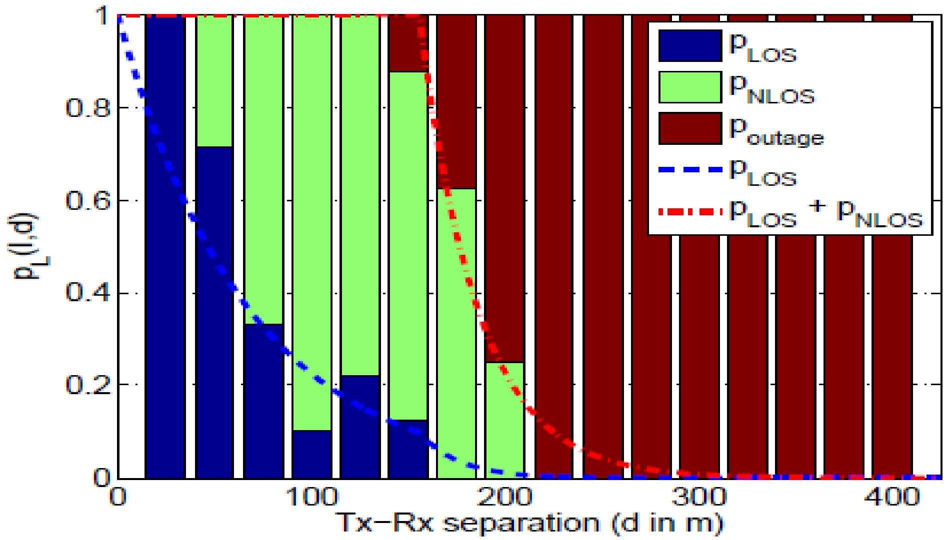
Isotropic Path Loss Comparison



S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges,” Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

- Isotropic NLOS path loss measured in NYC
  - ~ 20 - 30 dB worse than 3GPP urban micro model for fc=2.5 GHz
- Beamforming will more than offset this loss.
- Bottom line:
  mmW omni channels do not experience much path loss beyond the simple free space frequency dependence in urban New York City

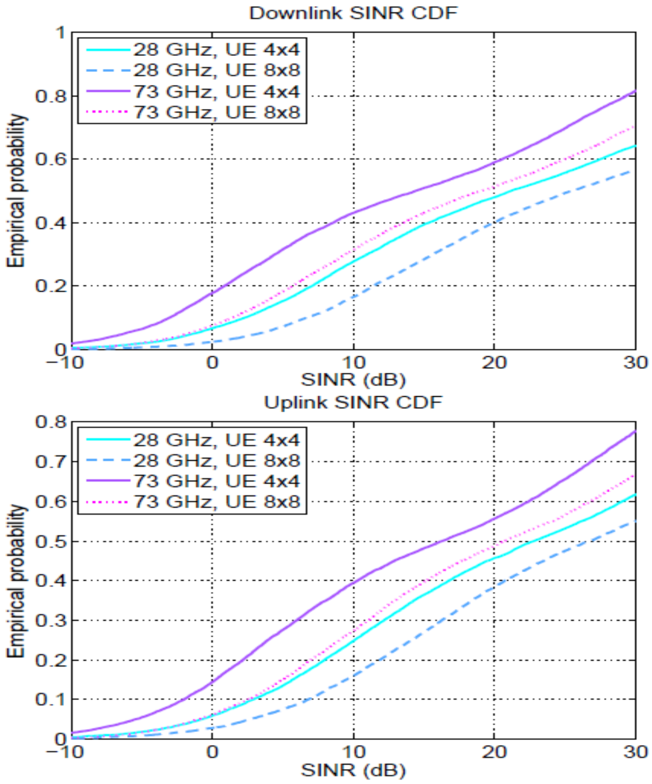
Hybrid LOS-NLOS-Outage Model



S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges,” Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

- mmW signals susceptible to severe shadowing.
  - Not incorporated in standard 3GPP models, but needed for 5G
- New three state link model: LOS-NLOS-outage
  - Other Outage modeling efforts (Bai, Vaze, Heath ‘13)
- Outages significant only at d > 150m
  - Will help smaller cells by reducing interference

Simulations: SNR Distribution



- Simulation assumptions:
  - 200m ISD
  - 3-sector hex BS
  - 20 / 30 dBm DL / UL power
  - 8x8 antenna at BS
  - 4x4 (28 GHz), 8x8 (73 GHz) at UE
- A new regime:
  - **High SNR on many links**
  - **Better than current macro-cellular**
  - **Interference is non dominant**

S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges,” Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

Comparison to Current LTE

- Initial results show significant gain over LTE
  - Further gains with spatial mux, subband scheduling and wider bandwidths

System antenna	Duplex BW	fc (GHz)	Antenna	Cell throughput (Mbps/cell)		Cell edge rate (Mbps/user, 5%)	
				DL	UL	DL	UL
mmW	1 GHz TDD	28	4x4 UE 8x8 eNB	1514	1468	28.5	19.9
		73	8x8 UE 8x8 eNB	1435	1465	24.8	19.8
Current LTE	20+20 MHz FDD	2.5	(2x2 DL, 2x4 UL)	53.8	47.2	1.80	1.94

10 UEs per cell, ISD=200m,
hex cell layout
LTE capacity estimates from 36.814

~ 25x gain

~ 10x gain

M. R. Akdeniz,Y. Liu, M. K. Samimi, S. Sun, S. Rangan, T. S. Rappaport, E. Erkip, “Millimeter Wave Channel Modeling and Cellular Capacity Evaluation,” IEEE. J. Sel. Areas on Comm., July 2014

Recent Results by Nokia for 73 GHz

* Assumes RF BW of 2.0 GHz, NCP-SC Modulation
* Symbol Rate 1.536 Gigasymbols/sec (50 X LTE)
* Access Point Array: 4 sectors, dual 4X4 polarization
* Ideal Channel State estimator and Fair Scheduler
* Beamforming using uplink signal

Simulation Results:

4X4 array: 3.2 Gbps (15.7 Gbps peak), 19.7% outage

8X8 array: 4.86 Gbps (15.7 Gbps peak), 11.5% outage

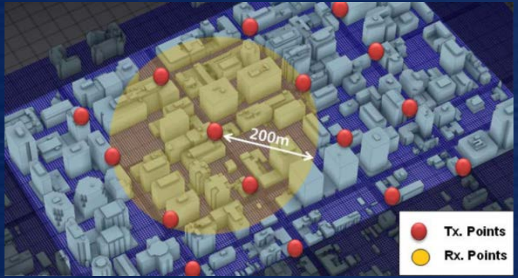
Outage can be reduced by denser cells, smart repeaters/relays

A. Ghosh,T. A. Thomas,M. Cudak, R. Ratasuk,P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, Jr., S. Sun, S. Nie, “Millimeter Wave Enhanced Local Area Systems: A High Data Rate Approach for Future Wireless Networks,” IEEE J. on Sel. Areas on Comm., July 2014.

Multi-Cell Analysis (1/2)

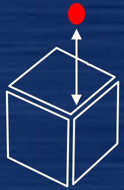
Ray-Tracing Simulation in Real City Modeling with Different Antenna Heights

Real City (Ottawa)

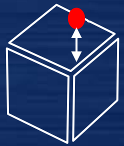


Antenna Height Scenario

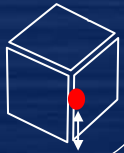
Scenario 1
30m above Rooftop



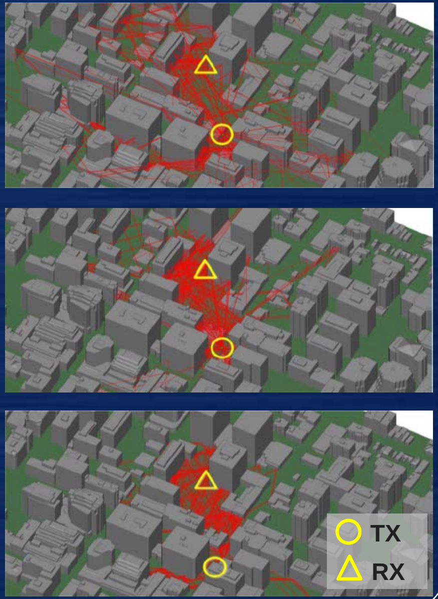
Scenario 2
5m above Rooftop



Scenario 3
10m above Ground



Ray-Tracing

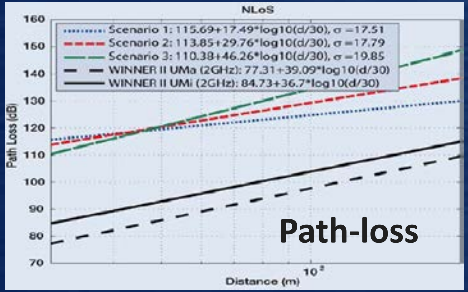


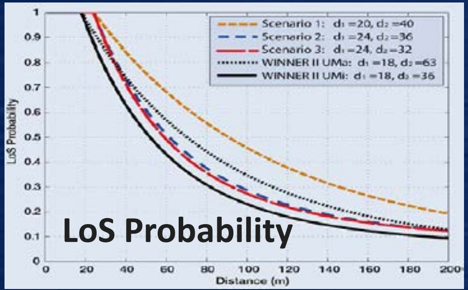
Multi-Cell Analysis (2/2)

Ray-Tracing based Channel Models and System Level Simulations

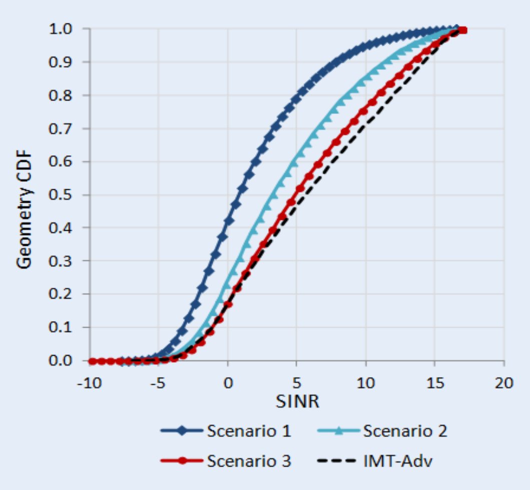
Scenario 3 (Higher Path-loss Exponent) gives better system performances in small cell deployment

Channel Models

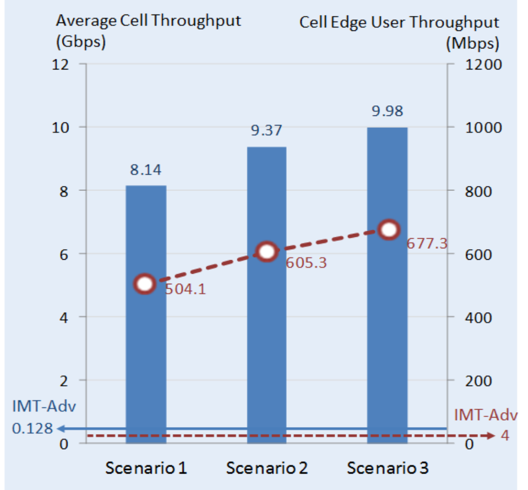




System Geometry



Avg. & Edge T'puts



Samsung's Vision

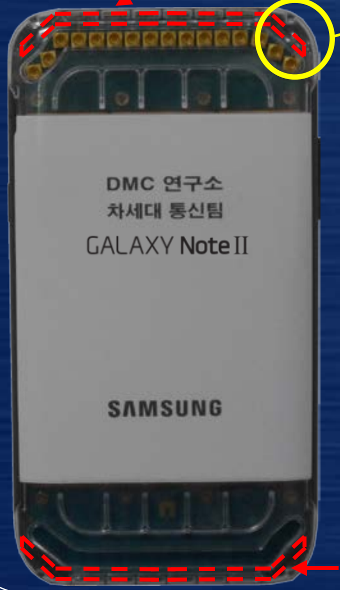
Mobile Device Feasibility – Antenna Implementation

SAMSUNG

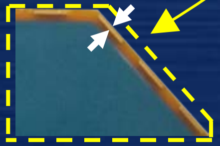
32 Elements Implemented on Mobile Device with "Zero Area" and 360º Coverage

"Zero Area" Design

16 Element Array



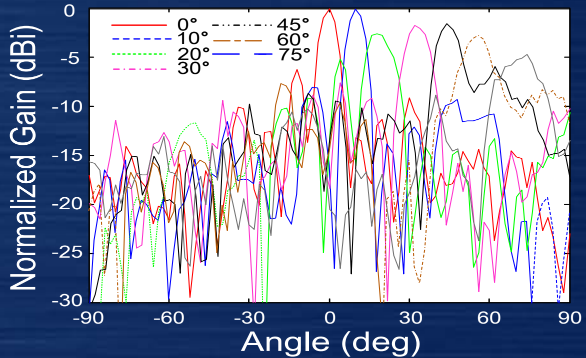
< 0.2 mm

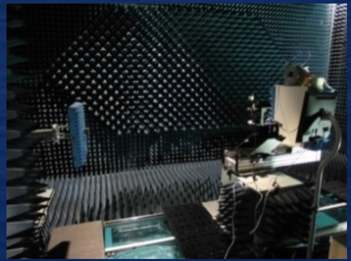


Negligible Area
for Antennas
In Edges

16 Element Array

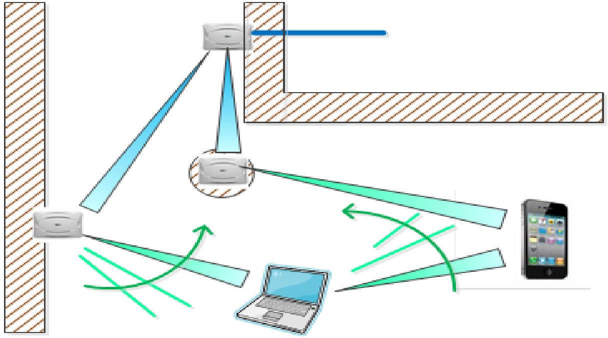
Measurement Results





Measured in
Anechoic Chamber

Multihop Relaying for mmW



- Significant work in multi-hop transmissions for cellular
- Gains have been minimal
- Why?
  - **Current cellular systems are bandwidth-limited**
  - **mmWave is noise-limited**
- Millimeter wave are different
  - Overcome outage via macrodiversity
  - Many degrees of freedom
  - Spatial processing / beamforming are key

Brooklyn 5G Summit Recap

April 24 – 25, 2014

Welcome Address by

Hossein Moiin
Chief Technology Officer (CTO) of NSN

John Stankey

Group President and Chief Strategy Officer, AT&T

Keynote : Better, Stronger, Faster: Unleashing the Next Generation of Innovation

US Spectrum Status for Higher Speed

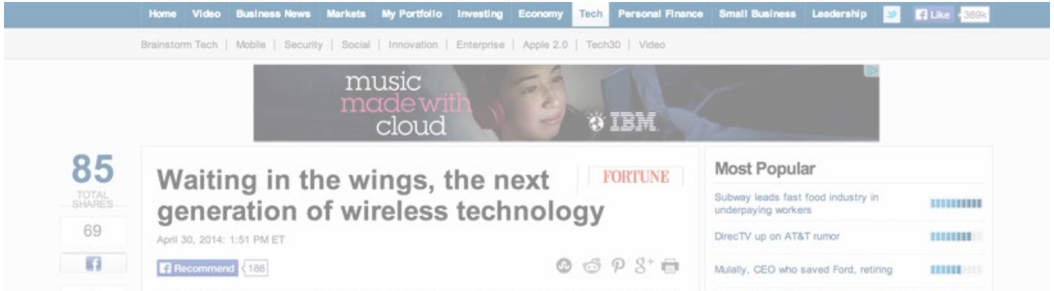
Michael Ha, FCC

The Press is taking note

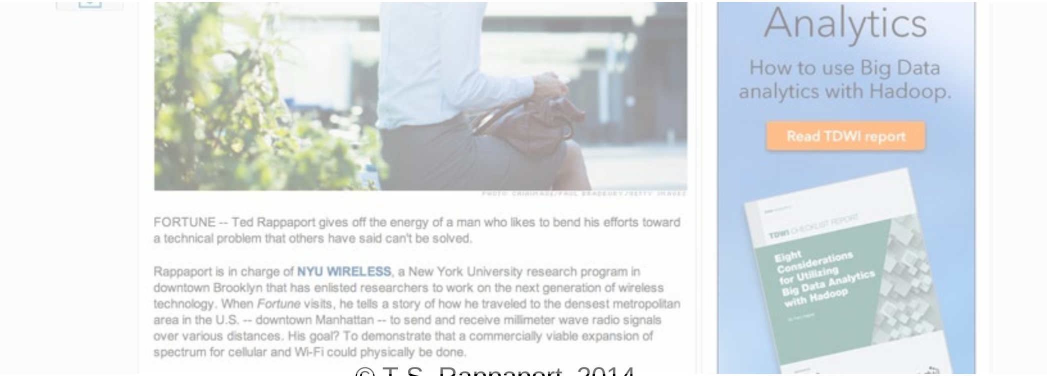
NYU POLYTECHNIC SCHOOL OF ENGINEERING

NYU WIRELESS

Fortune Magazine

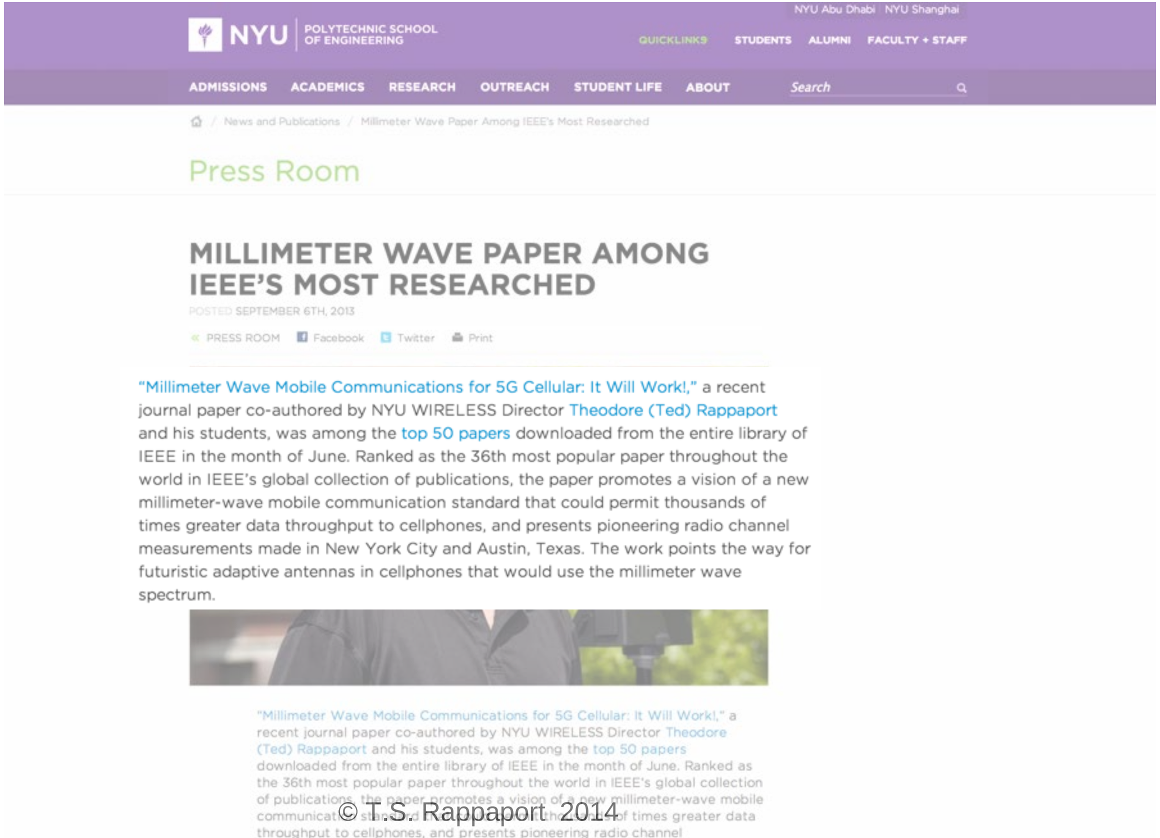


For now, the field is still in what Rappaport cheerfully calls a "pre-competitive" stage, where the industry is sharing support for research institutions around the world and putting its heads together around standards. Once the first product rolls off the production line, though, it's game on.



Industry and academia is paying attention

MILLIMETER WAVE PAPER AMONG IEEE'S MOST RESEARCHED



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MILLIMETER WAVE PAPER AMONG IEEE'S MOST RESEARCHED

POSTED SEPTEMBER 6TH, 2013

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"Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," a recent journal paper co-authored by NYU WIRELESS Director Theodore (Ted) Rappaport and his students, was among the top 50 papers downloaded from the entire library of IEEE in the month of June. Ranked as the 36th most popular paper throughout the world in IEEE's global collection of publications, the paper promotes a vision of a new millimeter-wave mobile communication standard that could permit thousands of times greater data throughput to cellphones, and presents pioneering radio channel measurements made in New York City and Austin, Texas. The work points the way for futuristic adaptive antennas in cellphones that would use the millimeter wave spectrum.

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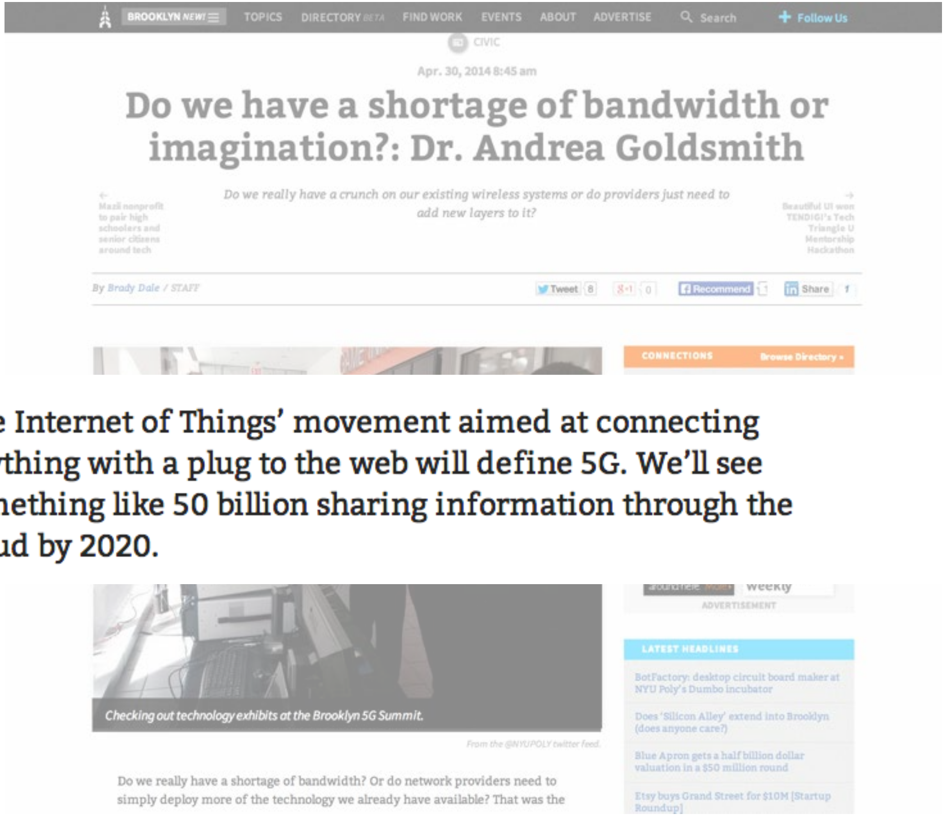
The Renaissance is before us

Technical.ly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CIVIC

Apr. 30, 2014 8:45 am

Do we have a shortage of bandwidth or imagination?: Dr. Andrea Goldsmith

Do we really have a crunch on our existing wireless systems or do providers just need to add new layers to it?

By Brady Dale / STAFF

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Checking out technology exhibits at the Brooklyn 5G Summit.

From the @NYUPOLY twitter feed.

Do we really have a shortage of bandwidth? Or do network providers need to simply deploy more of the technology we already have available? That was the

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Does 'Silicon Alley' extend into Brooklyn (does anyone care?)

Blue Apron gets a half billion dollar valuation in a $50 million round

Etsy buys Grand Street for $10M [Startup Roundup]

'The Internet of Things' movement aimed at connecting anything with a plug to the web will define 5G. We'll see something like 50 billion sharing information through the cloud by 2020.

Renaissance of Wireless

- mmW systems offer orders of magnitude capacity gains
- Experimental confirmation in NYC
  - 200 m cell radius very doable
  - Greater range extension through beam combining
  - Orders of magnitude capacity gains from increased bandwidth
  - Early days for channel modeling and adaptive arrays – a new frontier
  - NYU WIRELESS has created a Statistical Spatial Channel Model for 28 GHz – complete simulator
- Systems enter new regime:
  - Links are directionally isolated, high SNR, noise-limited channel
  - Links rely heavily on beamforming
  - Cooperation and base station diversity should offer big improvements
- What is old is new again!
  - Revisit old concepts, relays, channels, narrow beams -- mature concepts but now noise-limited

Millimeter wave Cellular – Early Days

- There is a lack of measurements and models at millimeter wave frequencies for outdoor cellular
- We found no outages for cells smaller than 200 m, with 25 dB gain antennas and typical power levels in Texas
- We continue to investigate New York City, for indoor and outdoor mmWave channels
- On-chip and integrated package antennas at millimeter wave frequencies will enable massive data rates, far greater than today's 4G LTE
- Massive investments will soon be made
- This an **exciting frontier** for the future of wireless,

Conclusion

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

•It took 30 years to go one decade in wireless carrier frequency (450 MHz to 5.8 GHz), yet we will advance another decade in the next year (5.8 to 60 GHz). By 2020, we will have devices well above 100 GHz and 20 Gbps in 5G and 6G cellular networks

•Millimeter Wave Wireless Communications offers a rich research field for low power electronics, integrated antennas, space-time processing, communication theory, simulation, networking, and applications – a new frontier

•The Renaissance of wireless is before us. Massive bandwidths and low power electronics will bring wireless communications into new areas never before imagined, including vehicles, medicine, and the home of the future

massively broadband ® is a registered trademark of Prof. Rappaport

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

To Zettabytes…and beyond

Acknowledgement to our Industrial Affiliates

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