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The Renaissance of Wireless Communications in the Massively Broadband ® Era

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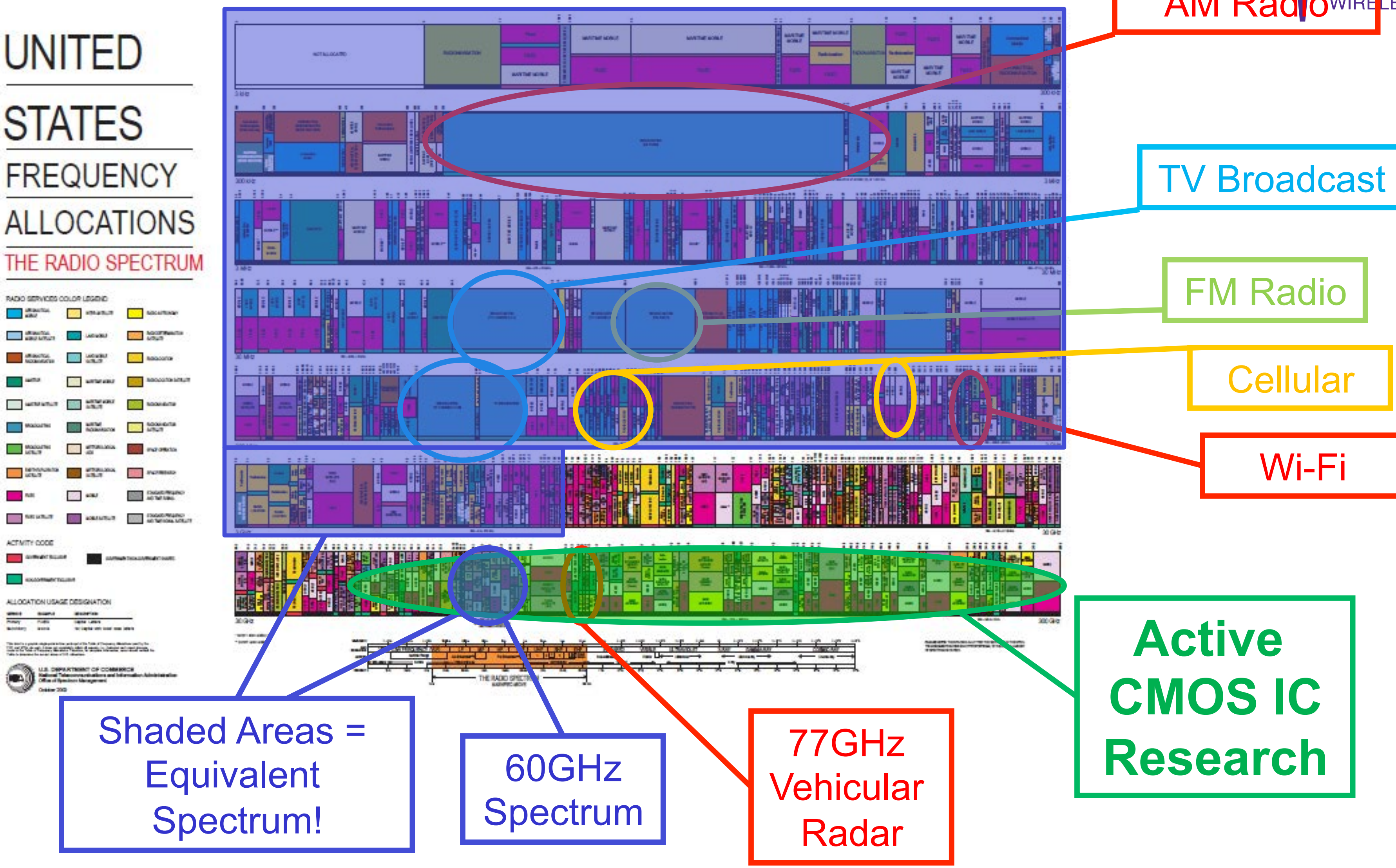
- Spectrum = real estate



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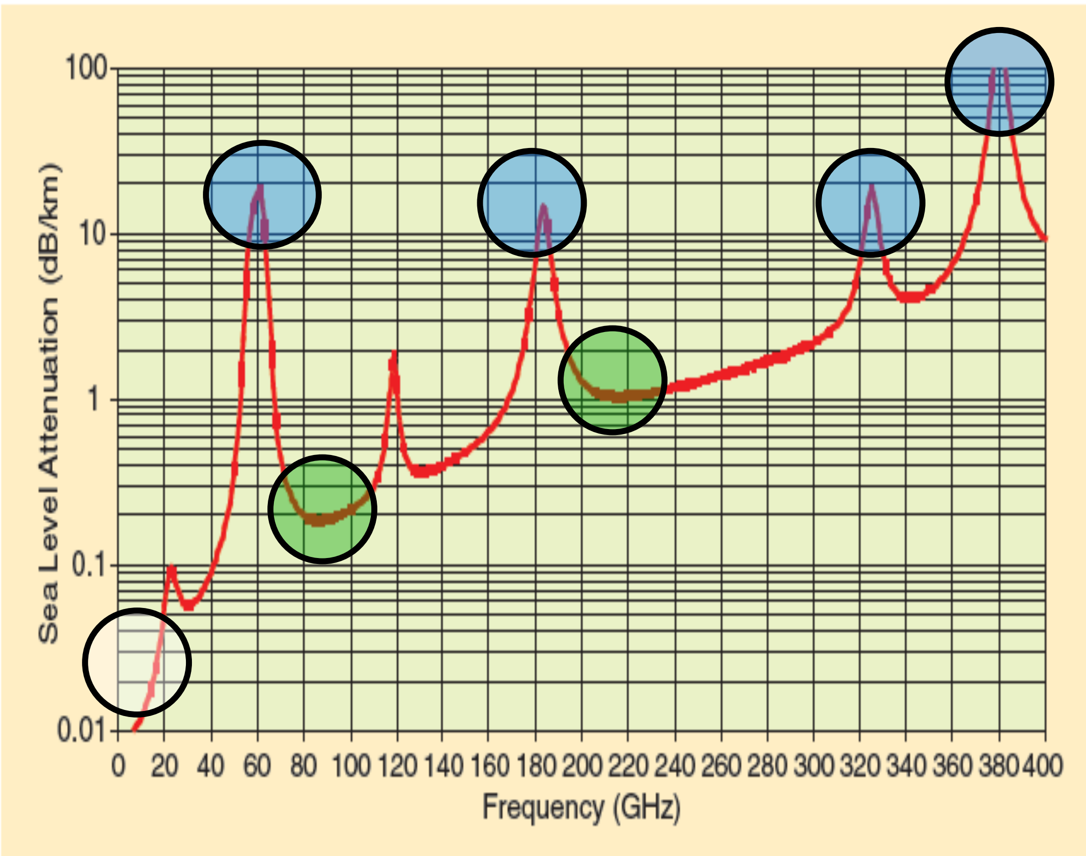
60 GHz and Above (sub-THz)
Important Short and Long Range Applications



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”

Spectrum Allocation History for 60GHz – Key mmWave Frequency Band

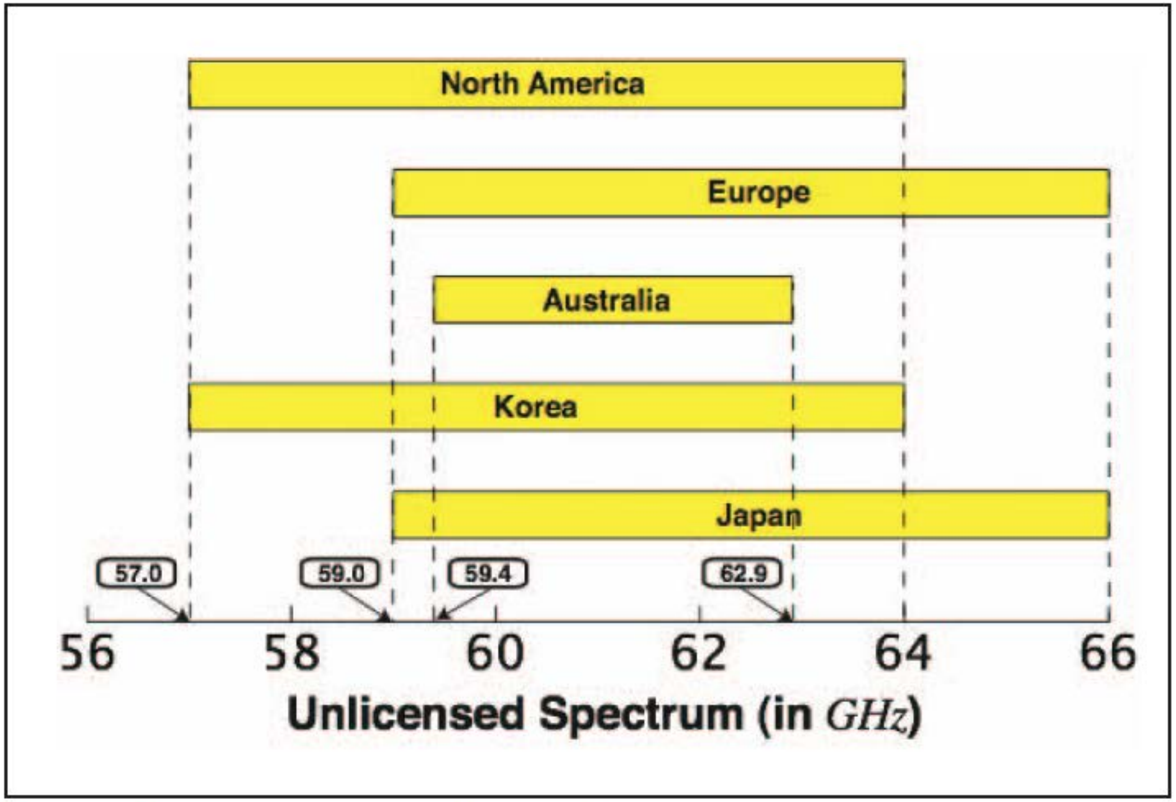


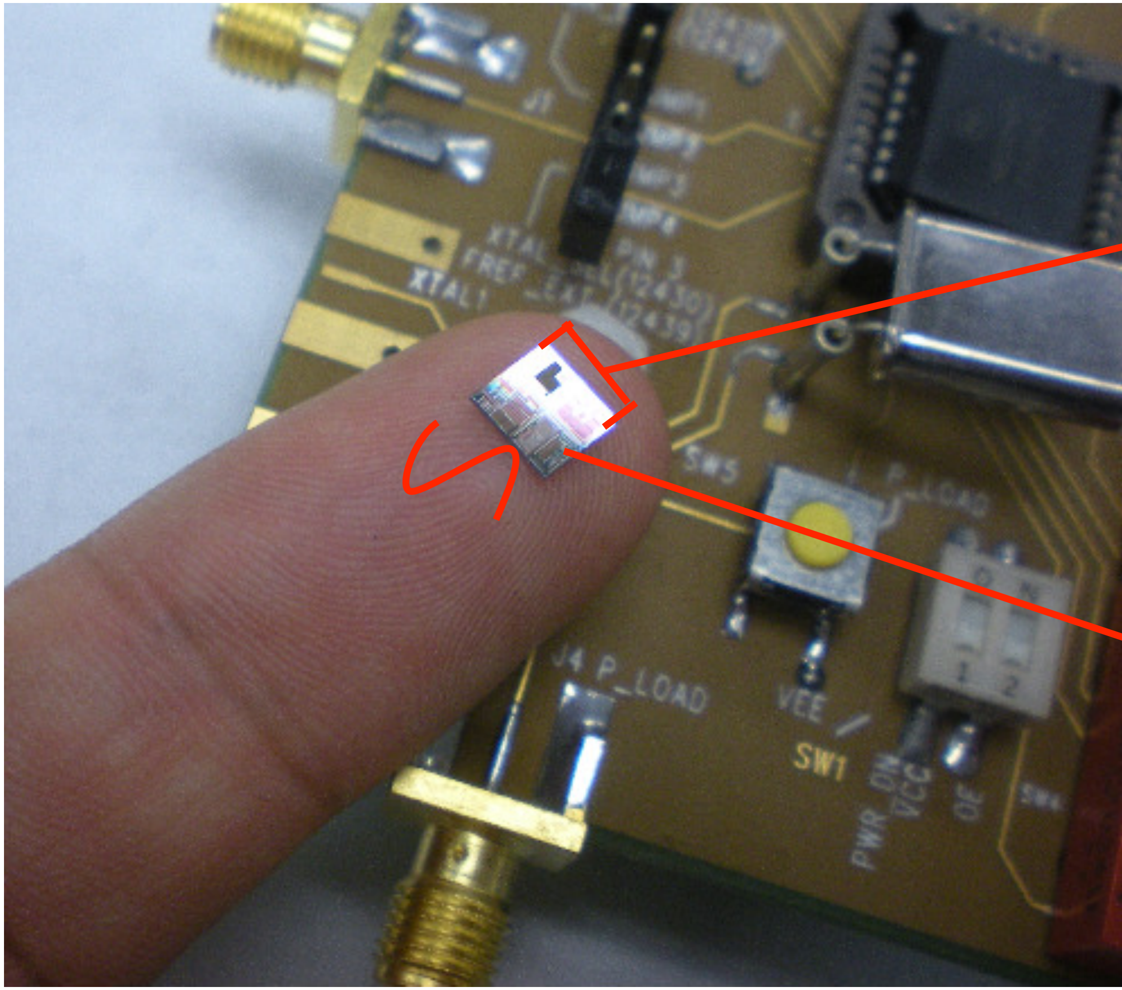
FIGURE 1 International unlicensed spectrum around 60 GHz.

- 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, http://sibeam.com/whtpapers/Background_on_Dev_of_60GHz_for_Commercial%20Use.pdf

mmWave Wavelength Visualization – 60GHz



5 millimeters

Integrated Circuit

mmWave and CMOS

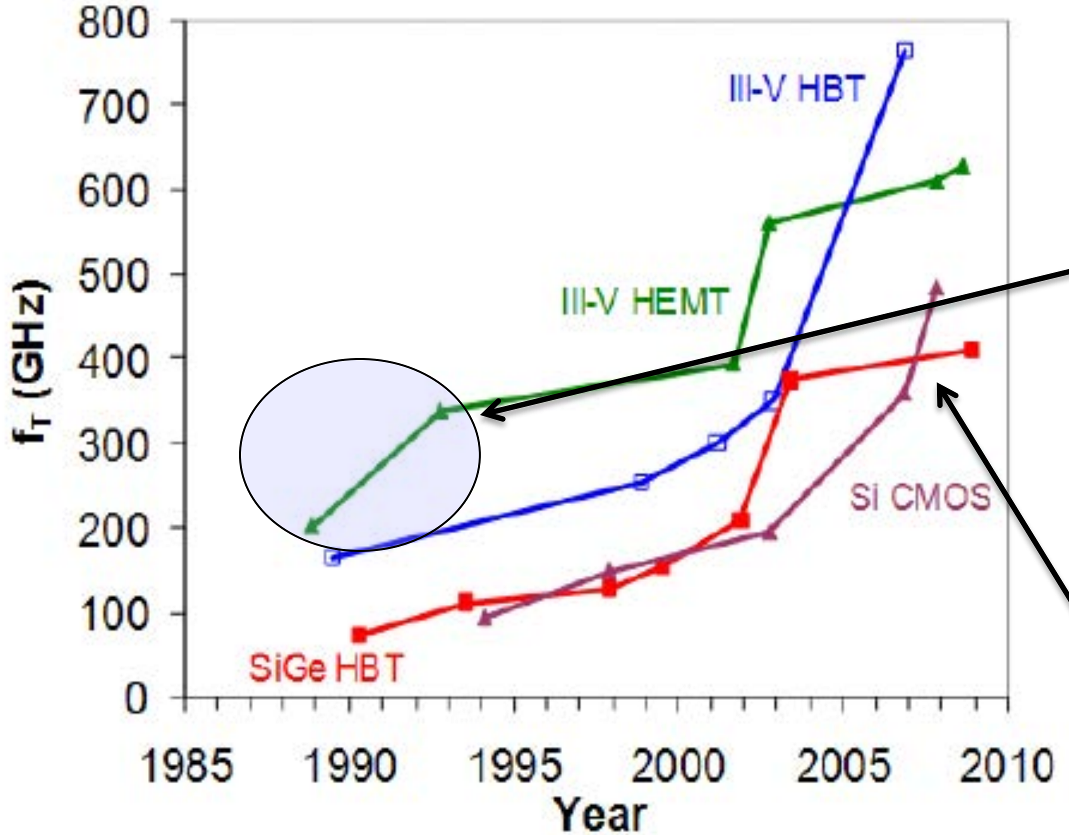


Fig. 4. Trend of the increase of operation frequency for various devices.

- III-V Technologies Are Expensive, Difficult to Integrate
- In Past, III-V Technologies only way to operate at mmWave Frequencies
- Graph Indicates that Silicon CMOS is approaching speed of expensive III-V Technologies
- CMOS gives **More Integration, Lower Cost**

Jae-Sung Rieh and Dong-Hyun Kim, "An Overview of Semiconductor Technologies and Circuits for Terahertz Communication Applications," *GLOBECOM Workshops, 2009 IEEE* , vol., no., pp.1-6, Nov. 30 2009-Dec. 4 2009.

Cellular and Wireless Backhaul

Trends:

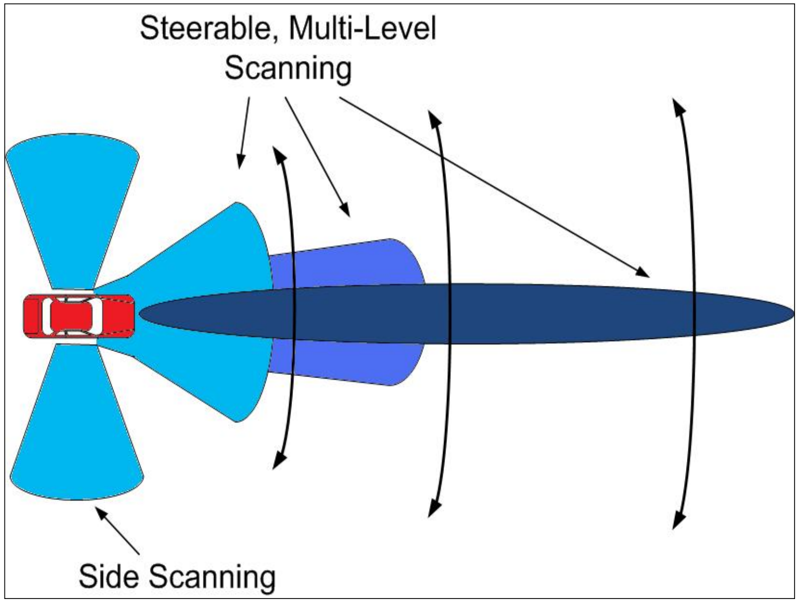
- Higher data usage
- Increase in base station density (femto/pico cells)
- Greater frequency reuse

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

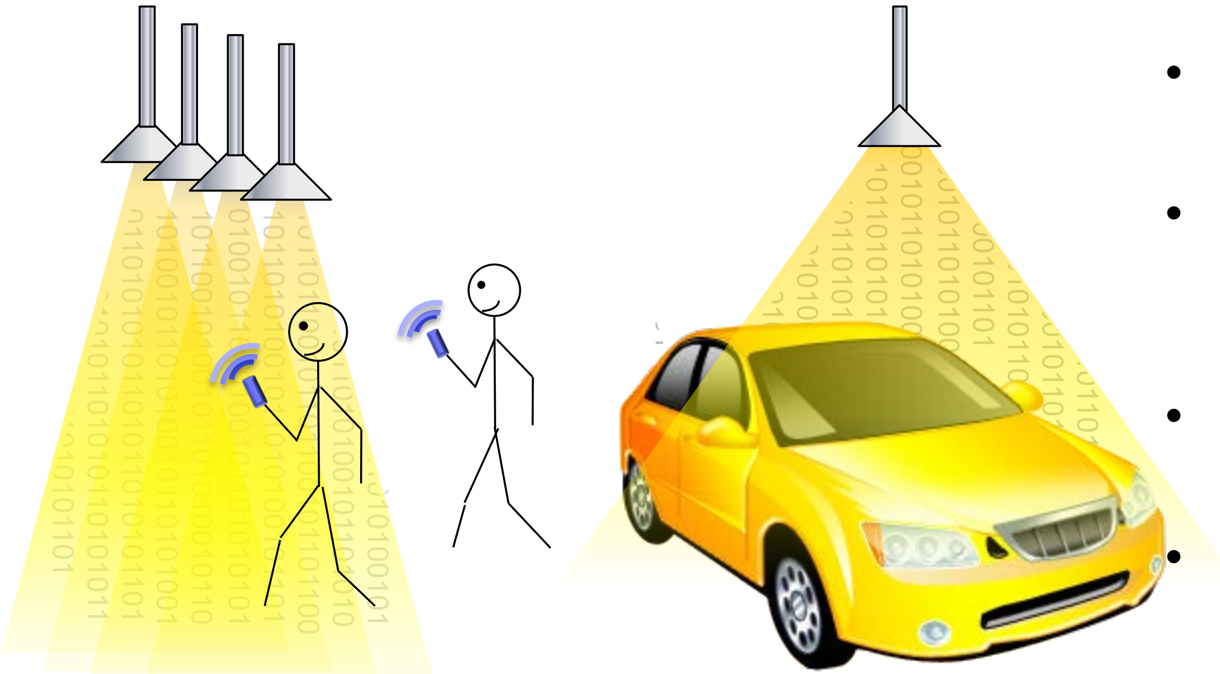
Solution: Cheap CMOS-based wireless backhaul with beam steering capability.

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



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.*

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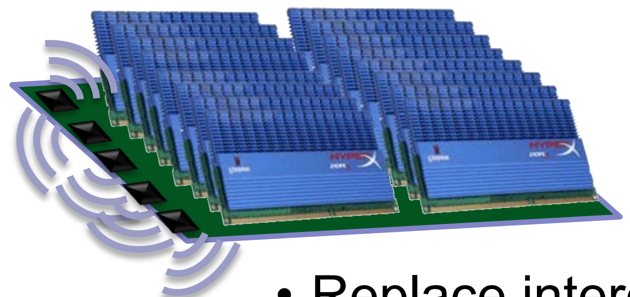
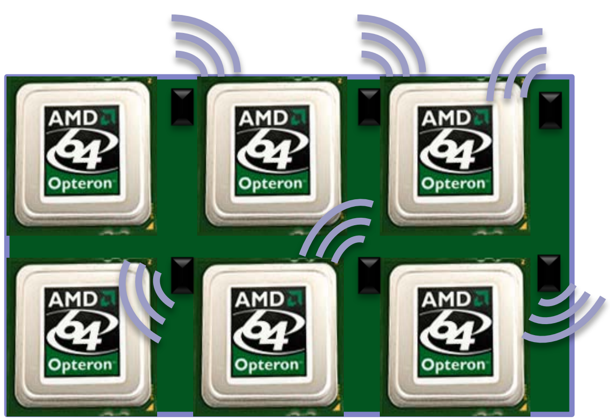
Future Applications

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

60 GHz Power Budget – Compare to Cable Link in Data Center

- A **wired** 10 meter link in a data center requires ~ 1 W of power
- Compare a **wireless** 60GHz link – **more flexible, less cost, same power**

60 GHz Power Budget	
Power dissipated before Transmitter PA (e.g. by Mixers, VCO, etc)	200mW
Power dissipated by Transmitter/Antenna PAs	200mW
Power dissipated in the channel/antennas	600mW
Overall Link Power 1W -- same as fiber/cable	

Park, M., "Applications and Challenges of Multi-band Gigabit Mesh Networks," Sensor Technologies and Applications, 2008., SENSORCOMM '08. Second International Conference, pp. 813-818 Aug 2008

J.N.Murdock, T. Rappaport, "Power Efficiency and Consumption Factor Analysis in Broadband Millimeter Wave Cellular Networks,," IEEE Global Communications Conf. December 2012.

mmWave 60 GHz Link Budget

Power Before Transmitter PA	1mW
Power Gain of Transmitter PA	20 (13dB)
Efficiency of Transmit Antenna	50% (3dB loss through antenna)
Gain of Transmit Antenna	1 (0dBi)
Transmitted Power	1mWx20x0.5x1 = 10mW (10dBm)
Path Loss for 1m and 5m Link	68dB @ 1m, 82dB @ 5m
Gain of Receive Antenna	1 (0dBi)
Efficiency of Receive Antenna	50% (3dB loss through antenna)
Received Power	-61dBm @ 1m, -75dBm @ 5m
Noise Power 10log(kTBNF) (B = 500MHz, NF = 6dB)	-77dBm
SNR	-61dBm + 77dBm = 16dB @ 1m -75dBm + 77dBm = 2dB @ 5m

Keynote Address "The Emerging World of Massively Broadband Devices: 60 GHz and Above," Delivered by T. S. Rappaport, Wireless at Virginia Tech Symposium, Blacksburg Virginia, June 3-5, 2009.
Park, M., "Applications and Challenges of Multi-band Gigabit Mesh Networks," Sensor Technologies and Applications, 2008., SENSORCOMM '08. Second International Conference, pp. 813-818 Aug 2008

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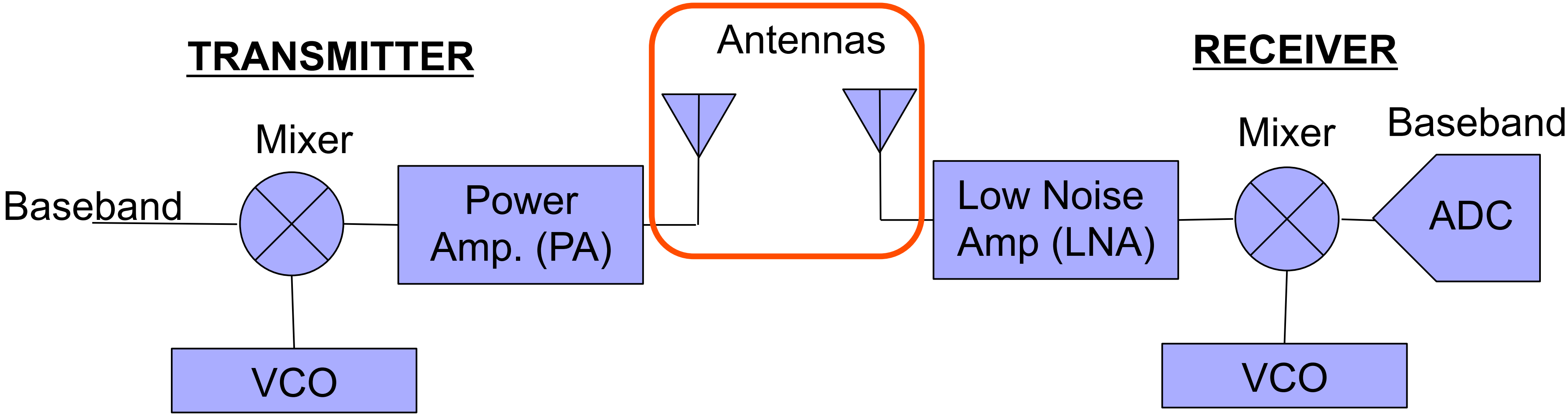
On-Chip Antennas for mmWave



- Motivation
- Challenges of On-Chip Antennas: Radiation into Substrate, Need for Material Parameters
- Different Antenna Topologies
- On-Chip Optimization: Dipole and Yagi Placement, Rhombic Arm Angle and Thickness
- Overcoming On-Chip Challenges: Techniques to Improve On-Chip Gain and Efficiency

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

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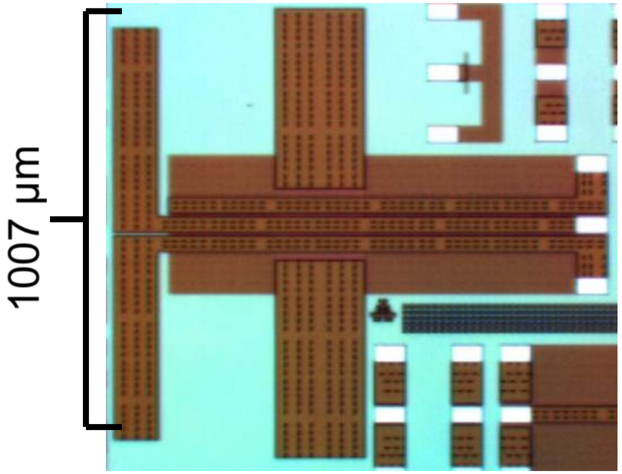
Beam Forming and Steering

- Antenna Size $\propto \lambda$
  - $\lambda = 5\,mm$ @ 60 GHz
  - $\lambda = 10\,mm$ @ 30 GHz
- A large antenna array can be constructed in reasonable form factor

60 GHz CMOS On-Chip Antenna designed by Rappaport Group

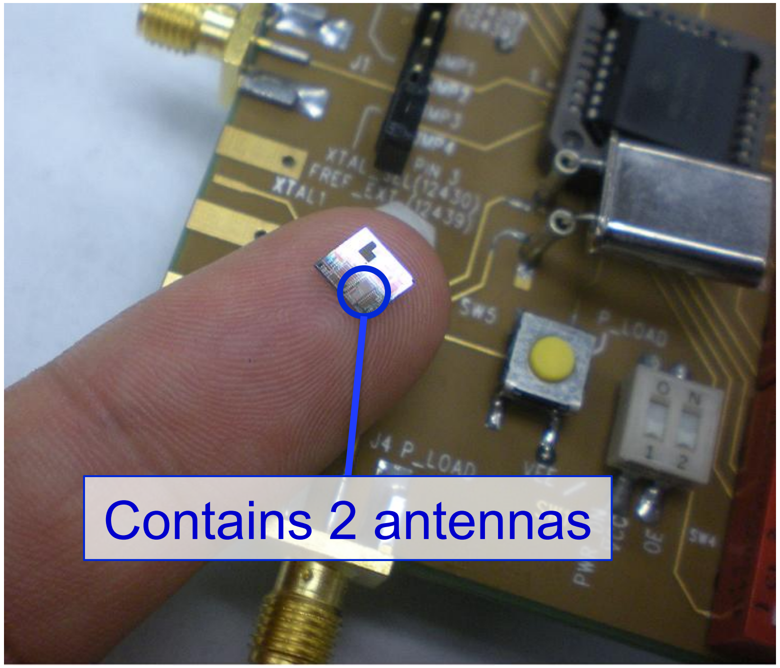


- Beamforming has been introduced into mmWave standards (e.g. IEEE 802.11ad)[1]
- Beam steering can be used to create a non-LOS link by reflecting off objects in the environment.

[1] C. Cordeiro, D. Akhmetov, M. Y. Park, "IEEE 802.11ad: Introduction and Performance Evaluation of the First Multi-Gbps WiFi Technology," Proc. ACM International Workshop on mmWave Communications, pp. 3-8, Sept. 2010.

Why On-Chip Antennas?

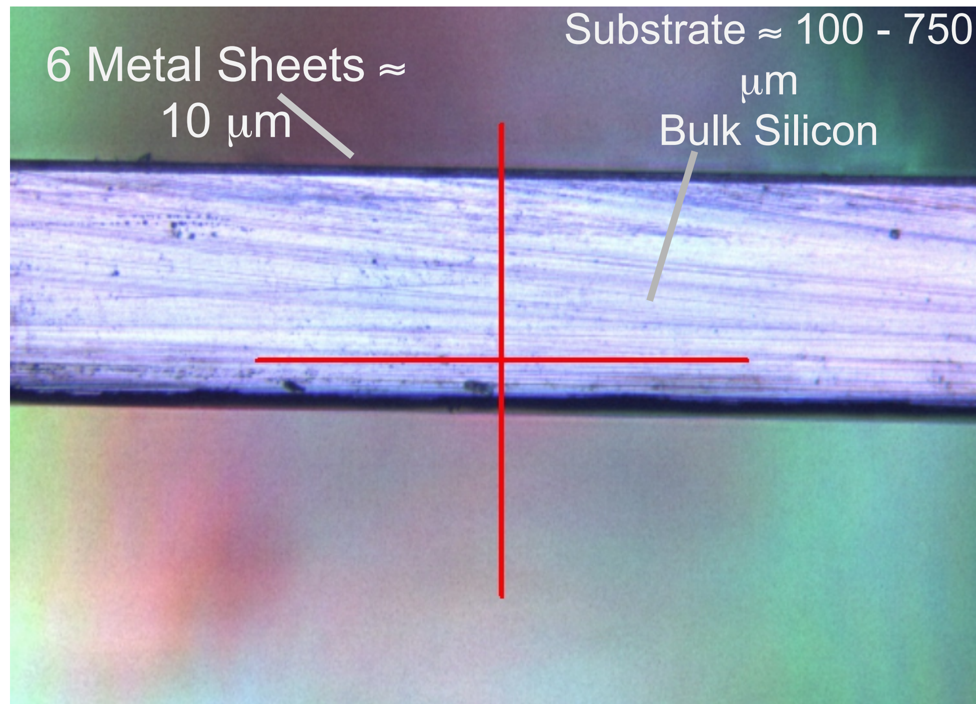
- Millimeter-Wave (mmWave) and THz signals have small wavelengths (λ)
  - Wavelength of mmWave Frequencies fit On-Chip!
- If immersed in dielectric, λ shrinks by sqrt (permittivity)
  - Example: permittivity of SiO2 $\approx$ 4 => wavelength in SiO2 $\approx$ 2.5mm
- Antenna sizes are comparable to integrated circuit (IC) sizes
- Tiny metal sheets available on ICs
  - Can be used to fabricate mmWave/ THz antennas
  - Enough IC area available for directional arrays
- Saves PCB real estate
  - (ex: handhelds, laptops, etc.)
- **Reduces fabrication costs**
- Pushes the bounds of integration



F. Gutierrez, S. Agarwal, and K. Parrish, "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.

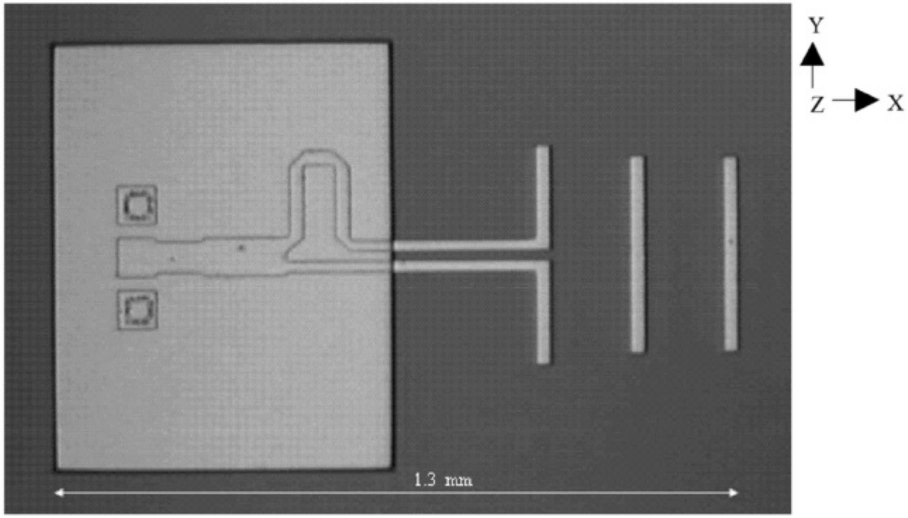
Substrate Radiation and Process

- New generations of CMOS = Higher doping concentration (less resistance to avoid latch up = turning on of parasitic BJT structures)
  - Higher doping = higher conductivity = lower efficiency
  - 180 nm = 10 Ω·cm, 45 nm = 0.1 Ω·cm
- High substrate conductivity increases substrate losses in the form of eddy currents for inductors and on-chip antennas.



Y. N. Robert Doering, Handbook of Semiconductor Manufacturing Technology, 2nd ed. CRC Press, 2008.
Gutierrez, F.; Rappaport, T.S.; Murdock, J. " Millimeter-wave CMOS On-Chip Antennas for Vehicular Electronic Applications, *72nd IEEE Vehicular Technology Conference Fall 2010*

On-Chip Antenna Topologies - Yagi



- Y.P. Zhang, M. Sun, L.H. Guo
- Yagi antenna on-chip
- Nanyang Technological University, Singapore (2005)
- Gain: -12.5 dBi
- Efficiency: 2%
- CMOS approximated with post-BEOL process @ 60 GHz
- 1.3 mm x .7 mm

Zhang, Y.P.; Sun, M.; Guo, L.H., "On-chip antennas for 60-GHz radios in silicon technology," *Electron Devices, IEEE Transactions on* , vol.52, no.7, pp. 1664-1668, July 2005

On-Chip Antenna Topologies – Planar Inverted F

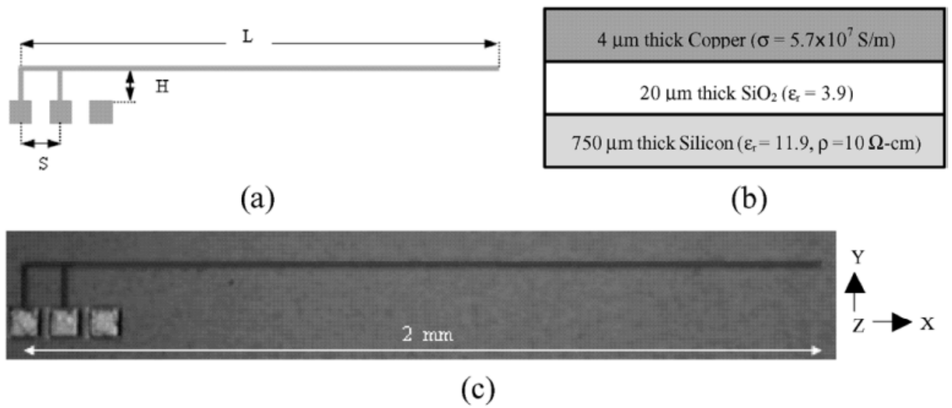
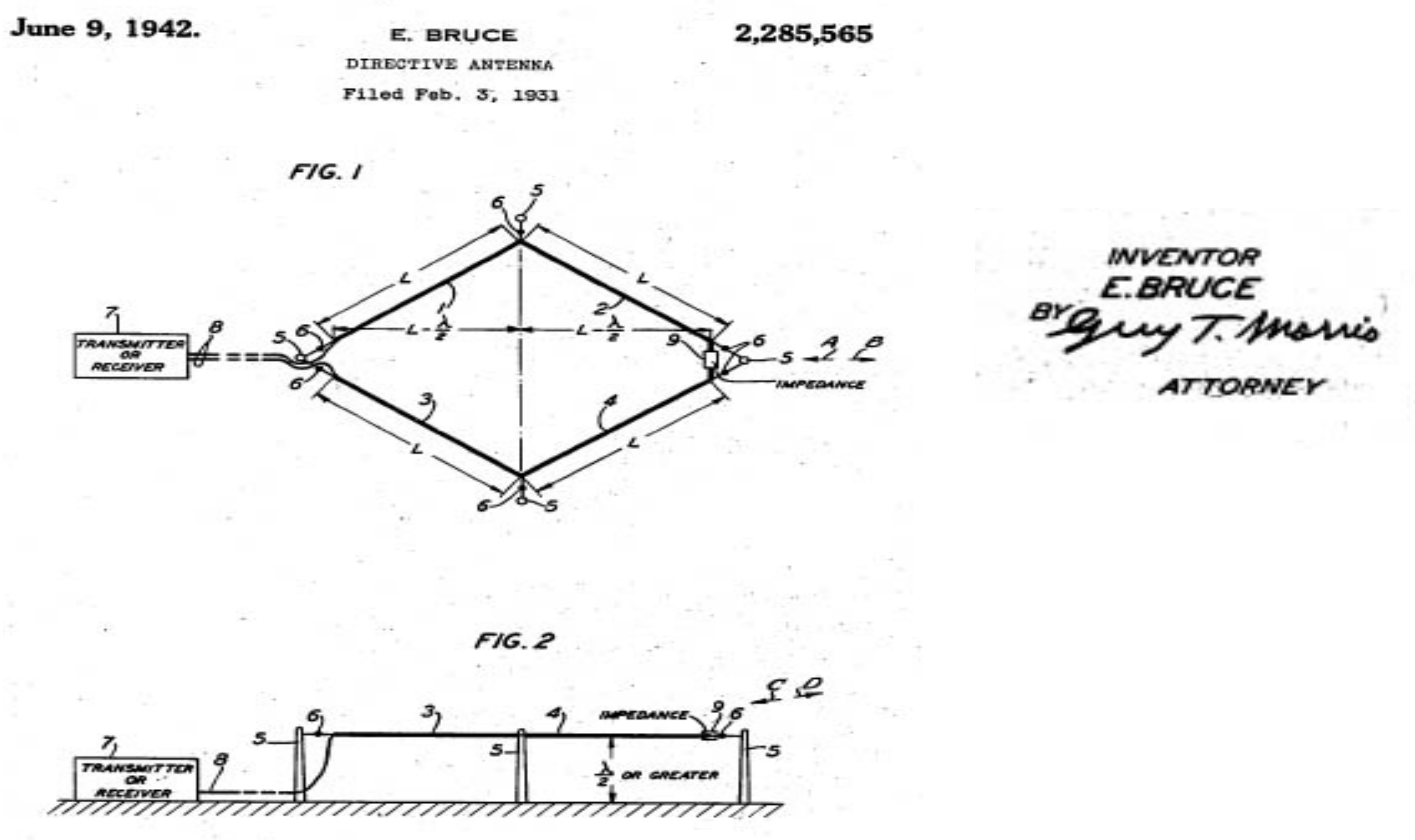


Fig. 1. On-chip inverted-F antenna: (a) layout, (b) cross-sectional view, and (c) top view photograph.

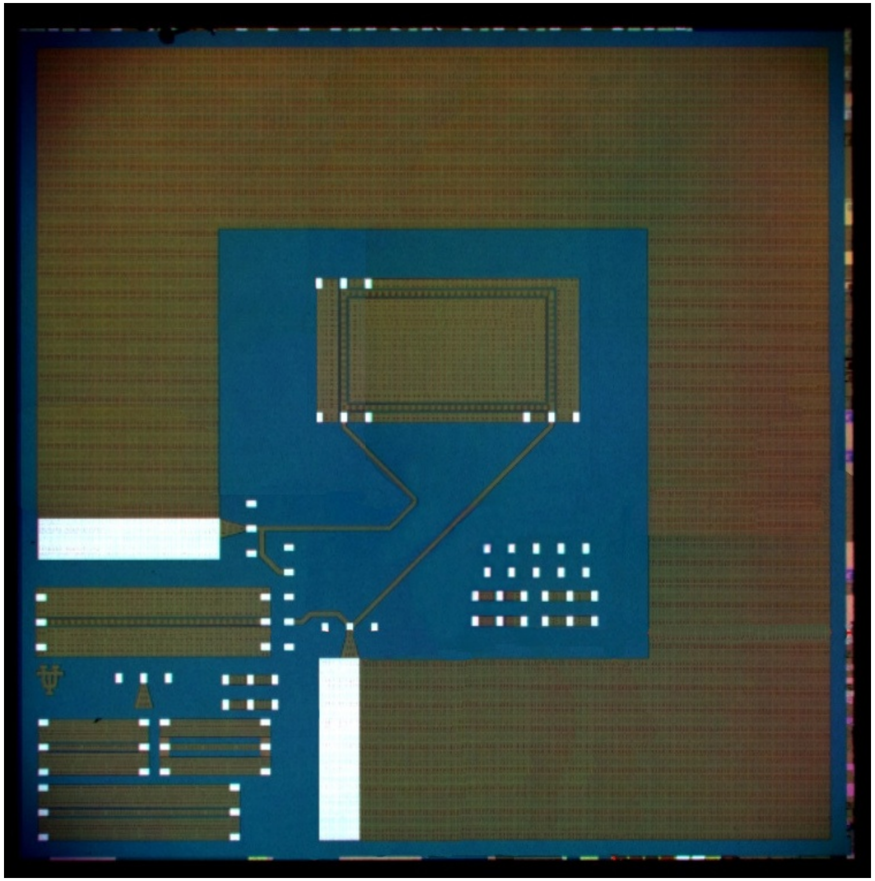
- Y.P. Zhang, M. Sun, L.H. Guo
- Planar Inverted F Antenna
- Nanyang Technological University, Singapore (2005)
- Gain: -19 dBi
- Efficiency: 1.7%
- CMOS with post-BEOL process @ 60 GHz
- 2 mm x 0.1 mm

Zhang, Y.P.; Sun, M.; Guo, L.H., "On-chip antennas for 60-GHz radios in silicon technology," *Electron Devices, IEEE Transactions on* , vol.52, no.7, pp. 1664-1668, July 2005

On-Chip Antenna Topologies - Rhombic



On-Chip Antenna Topologies - Rhombic



- F. Gutierrez, T. S. Rappaport, and J. Murdock of U. of Texas at Austin
- On-Chip Rhombic Antenna
- Balun for Single-Ended to Differential Conversion
- De-embedding Structures for Characterization
- 5mm x 5mm (each side of Antenna ≥ 2λ)
- TSMC 180nm Process for Low Substrate Conductivity (Lower Loss vs. Newer Processes)

F. Gutierrez, S. Agarwal, and K. Parrish, "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.

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Antenna Topologies - Comparison

Summary of Results

Antenna	Max Gain	Horizontal Gain	∠of Max Gain*	Efficiency	F/B	Approximate Area
Antennas developed in this paper						
Dipole	-7.3 dBi	-7.3 dBi	0°	9%	3 dB	0.13 mm^2
Yagi	-3.55 dBi	-3.8 dBi	20°	15.8%	10.4 dB	0.9 mm^2 (including spacing)
Rhombic	**-0.2 dBi**	**-1.27 dBi**	**39°**	**85%**	**3.7 dB**	**3.5 mm^2 (metal only)**
Past works						
Quasi-Yagi	-12.5 dBi			5.6%	"Poor"	
Inverted F	-19 dBi			3.5%		
CPW-Fed Yagi	-10 dBi			10%	9 dB	
Triangle	-9.4 dBi			12%		

•Y. Zhang, M. Sun, and L. Guo, "On-chip antennas for 60-GHz radios in silicon technology," IEEE Trans. on Electron Devices, vol. 52, no. 7, pp. 1664–1668, July 2005.
•S.-S. Hsu, K.-C. Wei, C.-Y. Hsu, and H. Ru-Chuang, "A 60-GHz Millimeter-Wave CPW-Fed Yagi Antenna Fabricated by Using 0.18m CMOS Technology," IEEE Electron Device Letters, vol. 29, no. 6, pp. 625–627, June 2008.
•C.-C. Lin, S.-S. Hsu, C.-Y. Hsu, and H.-R. Chuang, "A 60-GHz millimeter-wave CMOS RFIC-on-chip triangular Monopole Antenna for WPAN applications," IEEE Antennas and Propagation Society International Symposium, 2007, pp. 2522–2525, June 2007. F. Gutierrez, S. Agarwal, and K. Parrish, "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.
•F. Gutierrez, S. Agarwal, and K. Parrish, "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.

*above horizon

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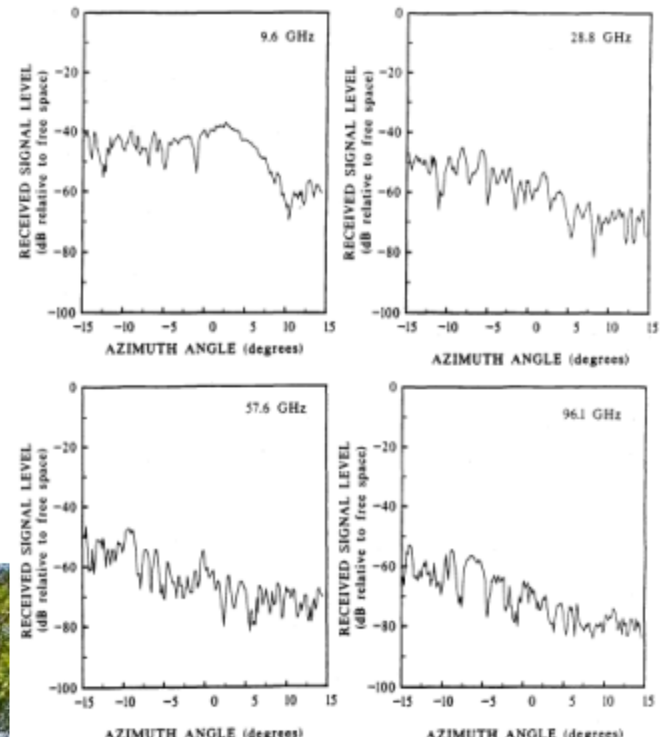
Will millimeter-wave Cellular work?

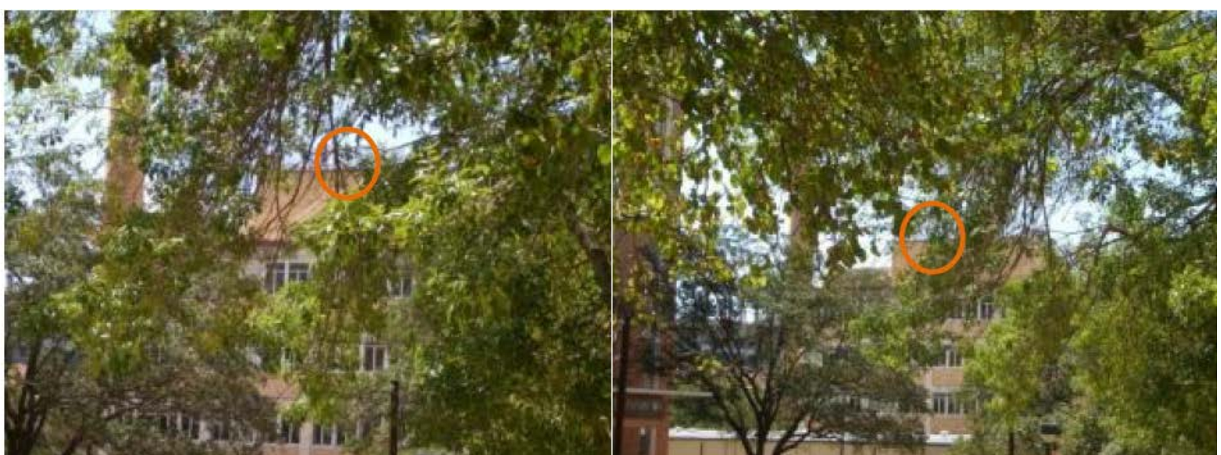
A look at past research

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%

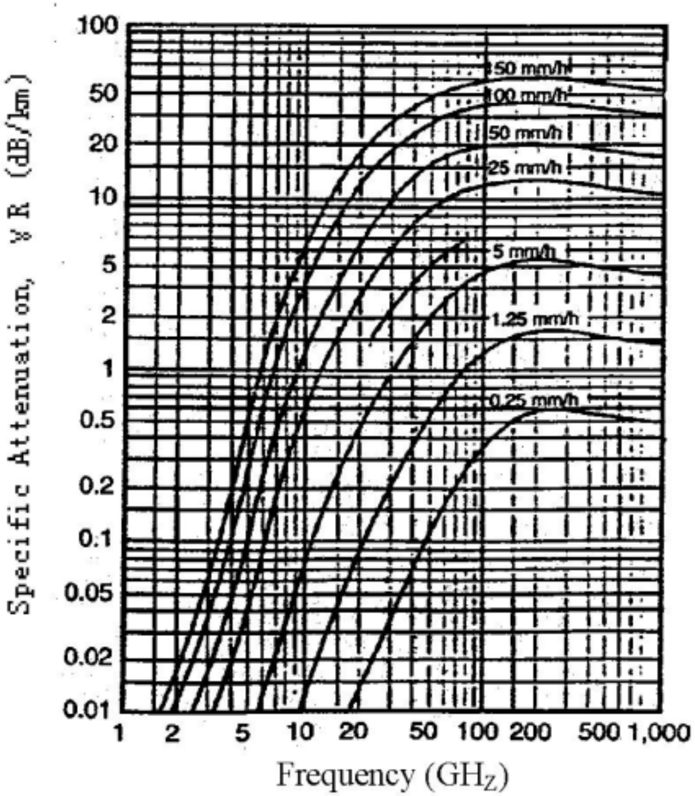
S.Y. Seidel and H.W. Arnold, "Propagation measurements at 28 GHz to investigate the performance of local multipoint distribution service (LMDS)," in IEEE Global Telecommunications Conference (Globecom), Nov. 1995, pp. 754-757.

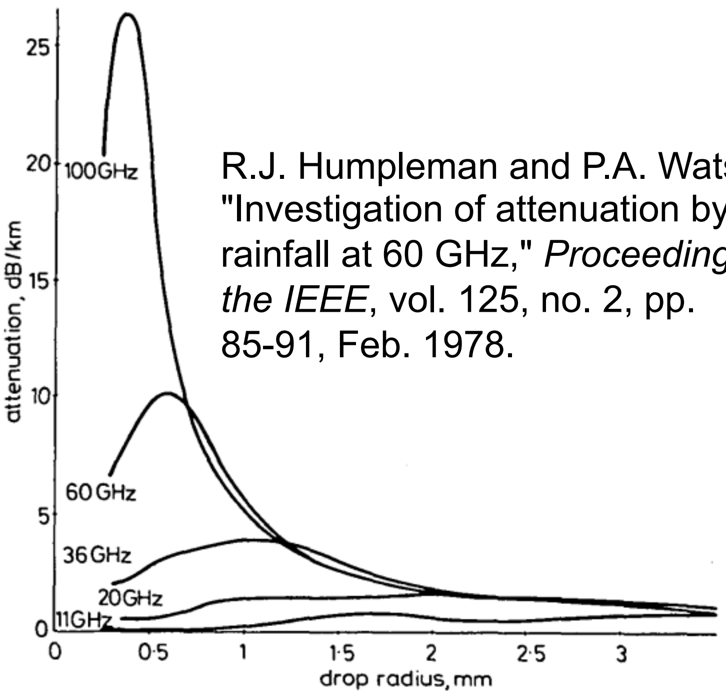
- Seidel measured signal strength up to 5 km for wireless backhaul at 28 GHz
- Coverage area increases with receiver antenna height
- Receiver antenna scanned only in azimuth direction
- Our study showed *elevation* angle scanning increases coverage significantly

Past Research – Rain Attenuation

- Zhao et al. (left figure) show the increase of rain attenuation with frequency
- Humpleman et al. (right figure) explain increase in scattering when the wavelength is smaller than the rain drop size

Q. Zhao and J. Li, "Rain Attenuation in Millimeter Wave Ranges," *Inter. Symp. on Antennas, Propagation & EM Theory*, 2006.





R.J. Humpleman and P.A. Watson, "Investigation of attenuation by rainfall at 60 GHz," *Proceedings of the IEEE*, vol. 125, no. 2, pp. 85-91, Feb. 1978.

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Channel Path Loss

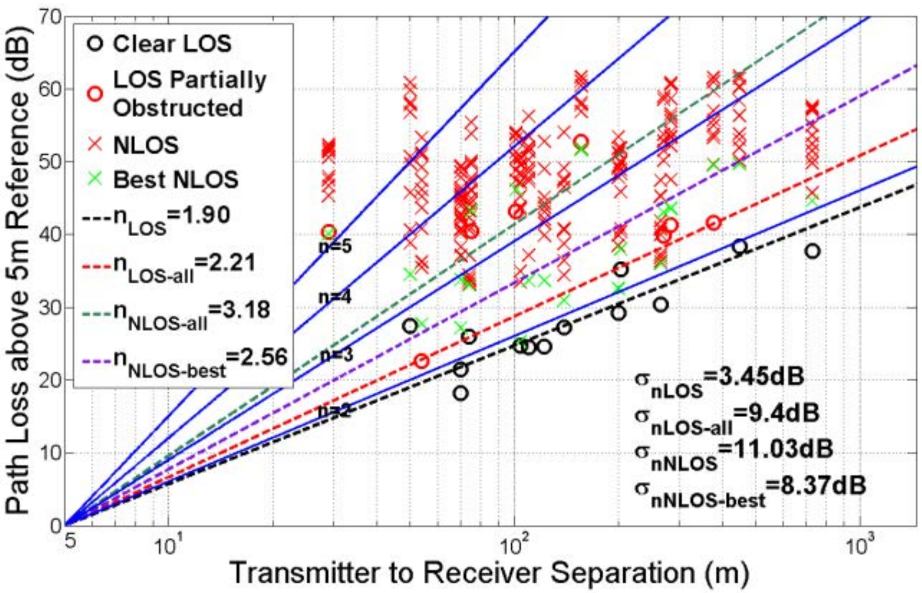
- Path loss is important to estimate SNR and CIR at receiver
- Important in determining cell sizes
- Log-normal shadowing model is most commonly used

$$PL = PL_0 + 10 n \log(d/d_0) + X_\sigma$$

PL_0 is path loss measured at close-in distance d_0

X_σ is a Gaussian random variable with standard deviation of σ that estimates the shadowing

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



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Multipath Excess Delay

- Excess Delay is propagation time at which multipath component reaches receiver after the first path.
- Important for equalization, cyclic prefix

Mean Excess Delay

$$\bar{\tau} = \frac{\sum_i P_i \tau_i}{\sum_i P_i}$$

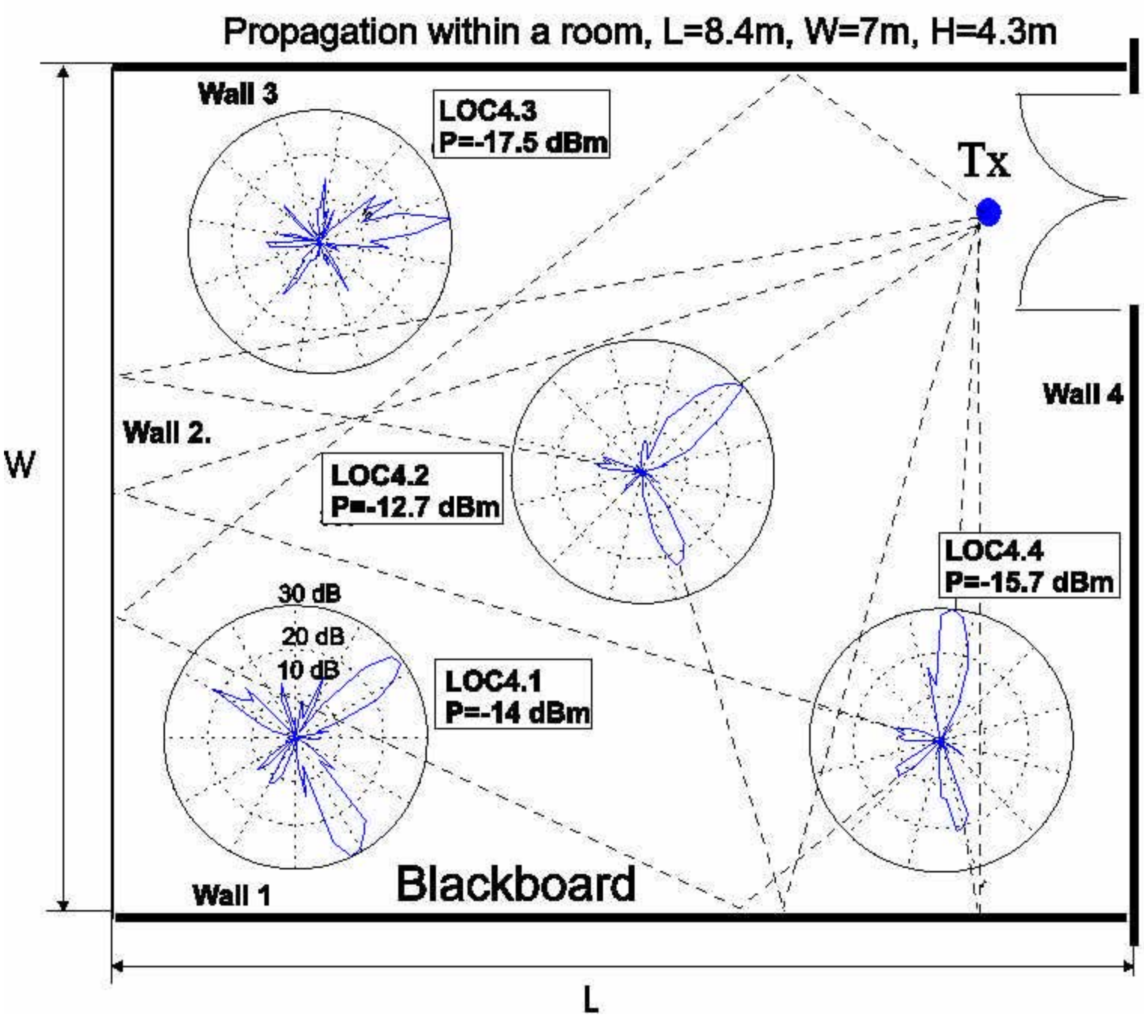
τ_i = Excess delay at time point i
P_i = Power at time point i

RMS Delay Spread

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$

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

Angle of Arrival (AOA) Profiles

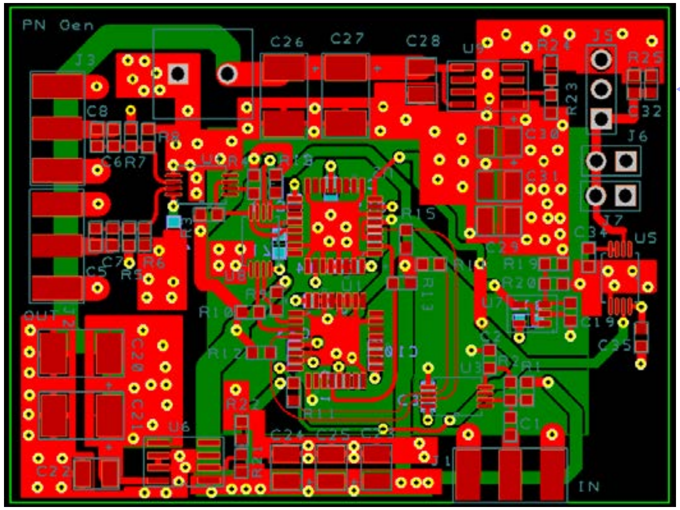


- AOA measurements are polar plots of received signal power versus receiver rotation angle.
- AOA data necessary for proper design of antenna array or switched beam antenna applications.

H. Xu, V. Kukshya, T. S. Rappaport, "Spatial and Temporal Characteristics of 60 GHz Indoor Channels," *IEEE Journal on Selected Areas in Communications*, Vol. 20, No. 3, April 2002, pp. 620 -630.

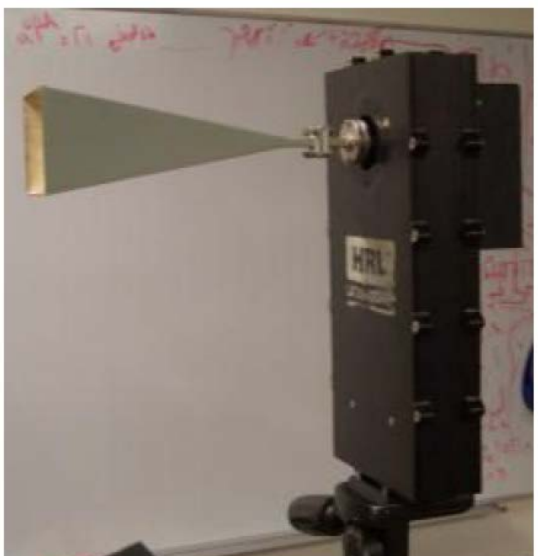
How to measure outdoor millimeter wave cellular channels?

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

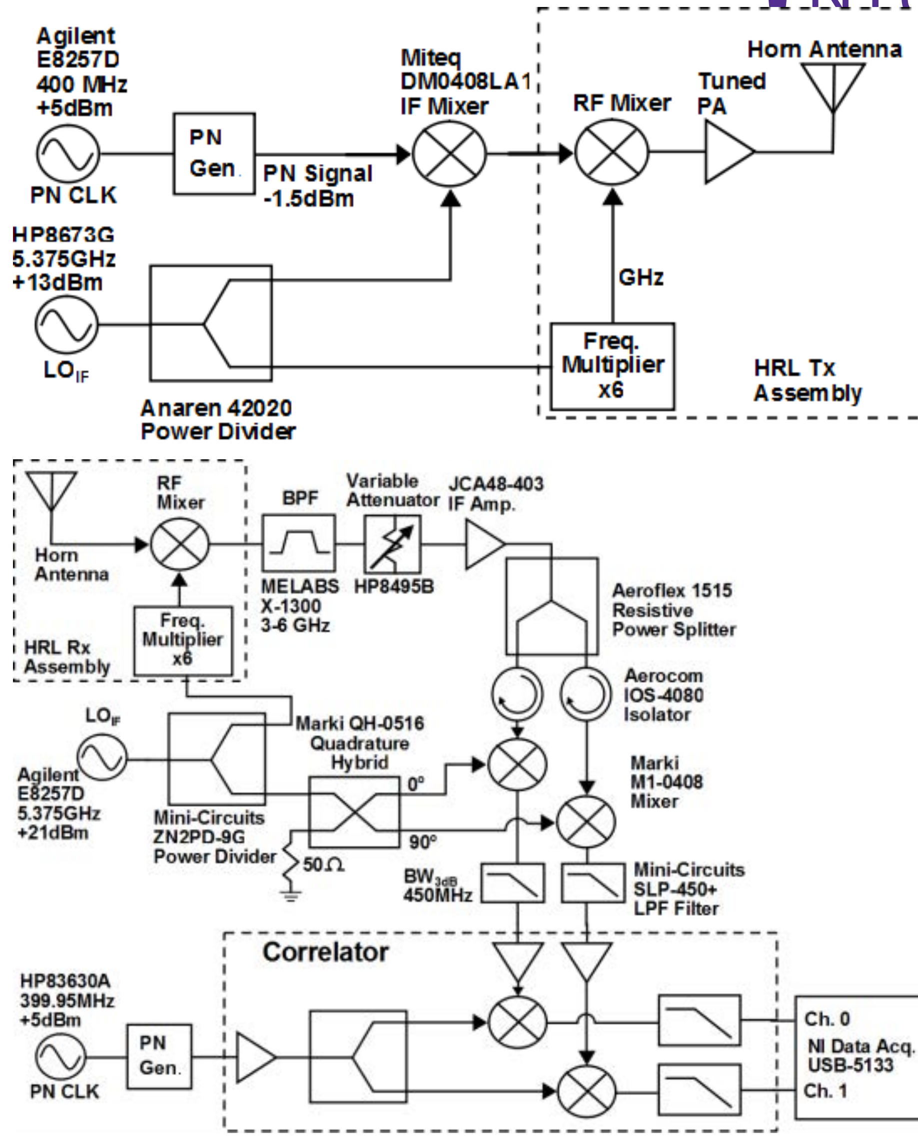
Sliding Correlator Hardware

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



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Radio propagation measurement results for 5G cellular

P2P and cellular outdoor at 38 and 60 GHz

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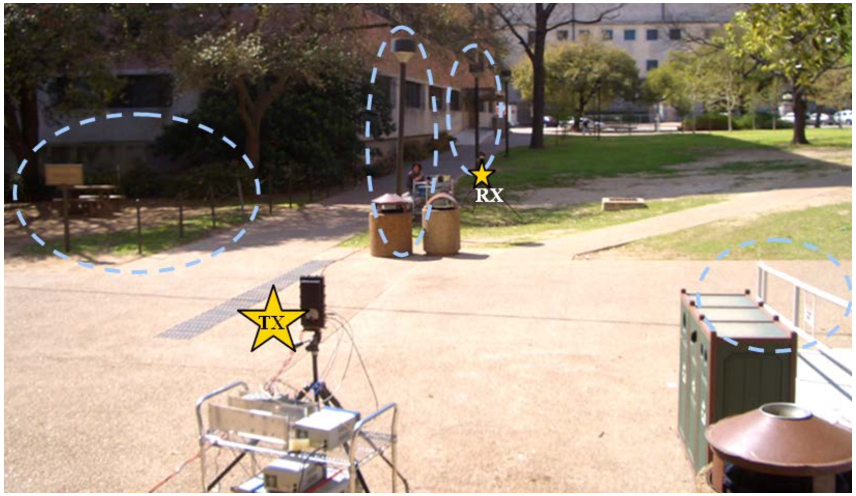
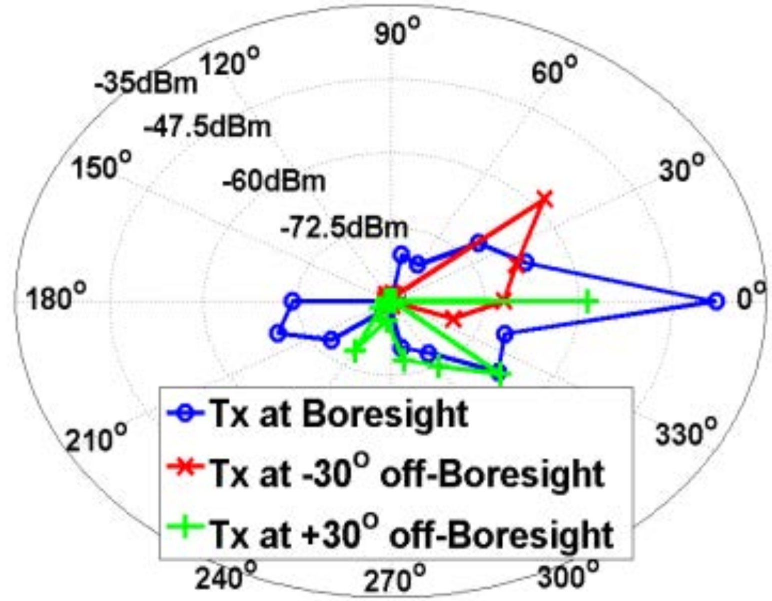
2011 Measurements at University of Texas

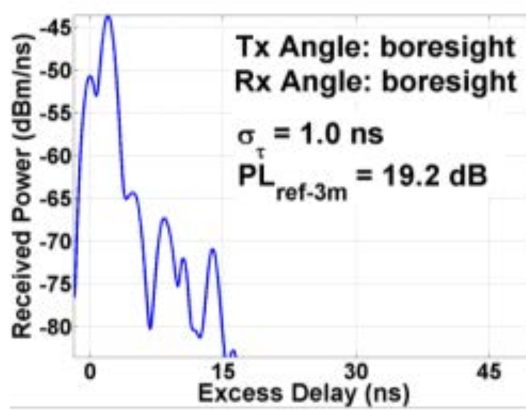
- Peer-to-Peer 38 and 60 GHz
  - Antennas 1.5m above ground
  - Ten RX locations (18-126m TR separation)
  - Both LOS and NLOS links measured using 8^{o} BW 25dBi gain antennas
- Cellular (rooftop-to-ground) at 38 GHz
  - Four TX locations at various heights (8-36m above ground) with TR separation of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

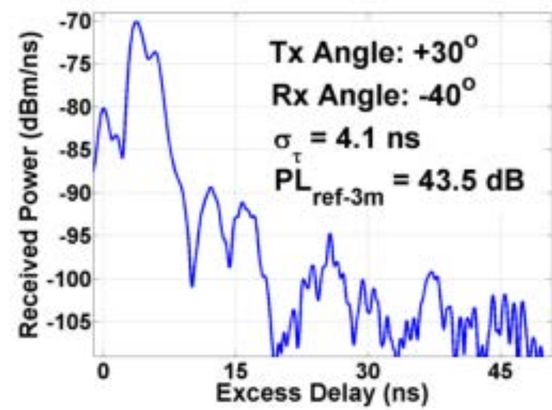
60 GHz AOA P2P Measurements



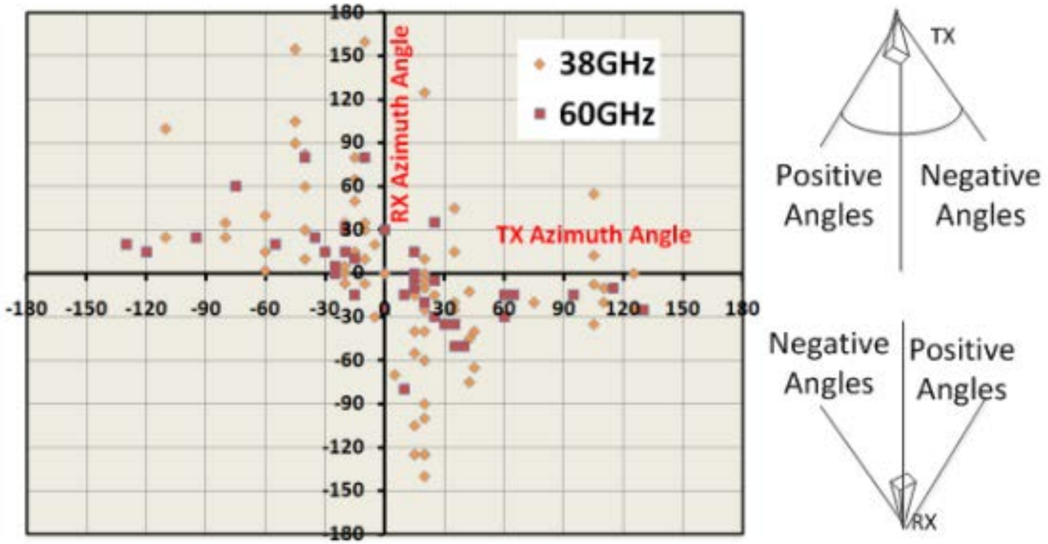


- **Observation**: Links exist at only few angles
- Thus, full AOA is not needed to characterize channel
- Only angles that have a signal are measured





Peer-to-Peer Angle of Arrival



- Links made at large range of receiver and transmitter angles
- Many scatterers near both RX and TX when placed 1.5m above ground
- Antenna Beam-steering can help make several NLOS links
- Objects, such as brick, reflect 38 GHz better than 60 GHz due to lower diffusive scattering

Cellular Measurement Map

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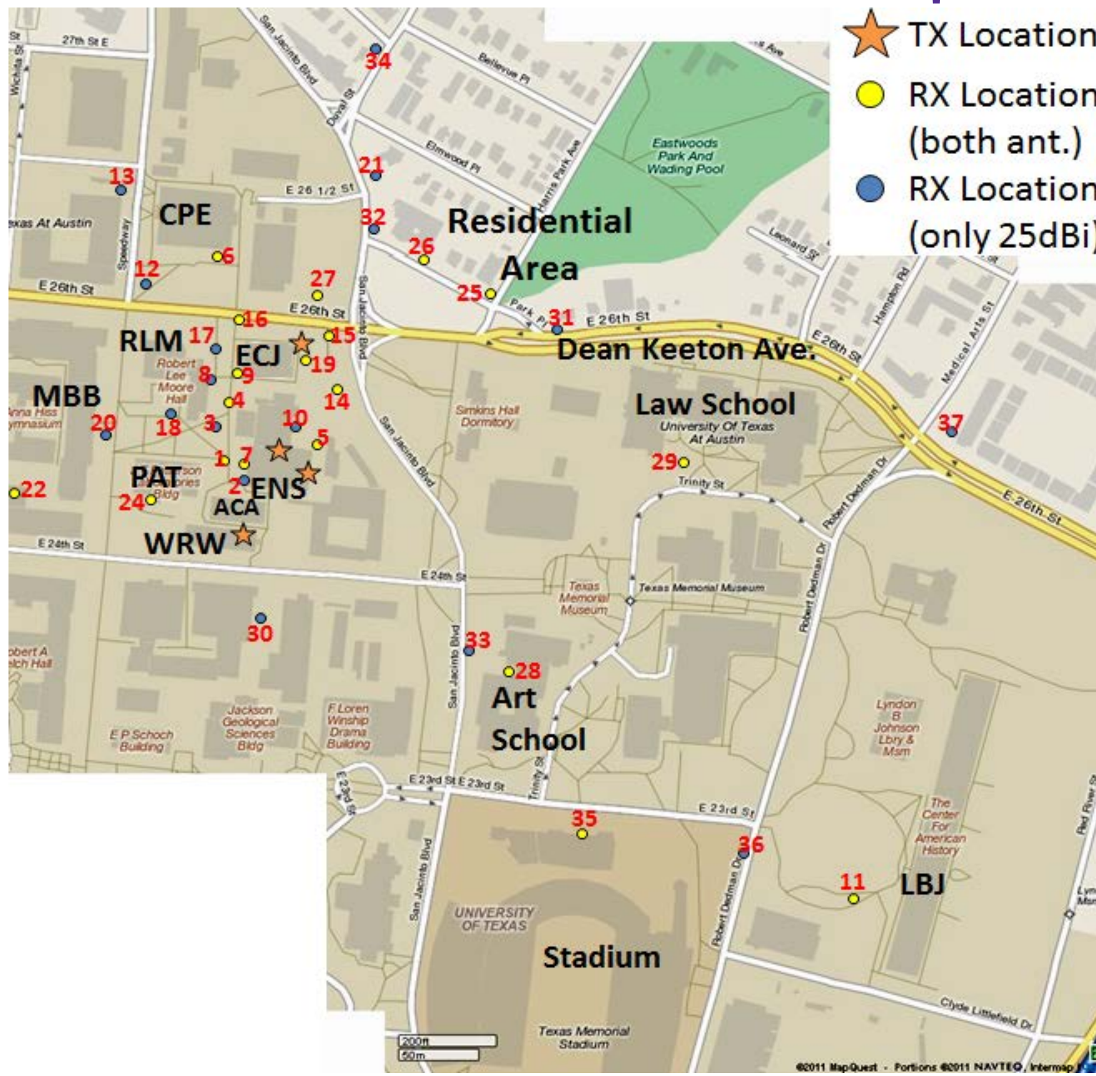
Transmitter Locations

WRW-A ENS-A

ECJ ENS-B



Sample Outdoor Environments

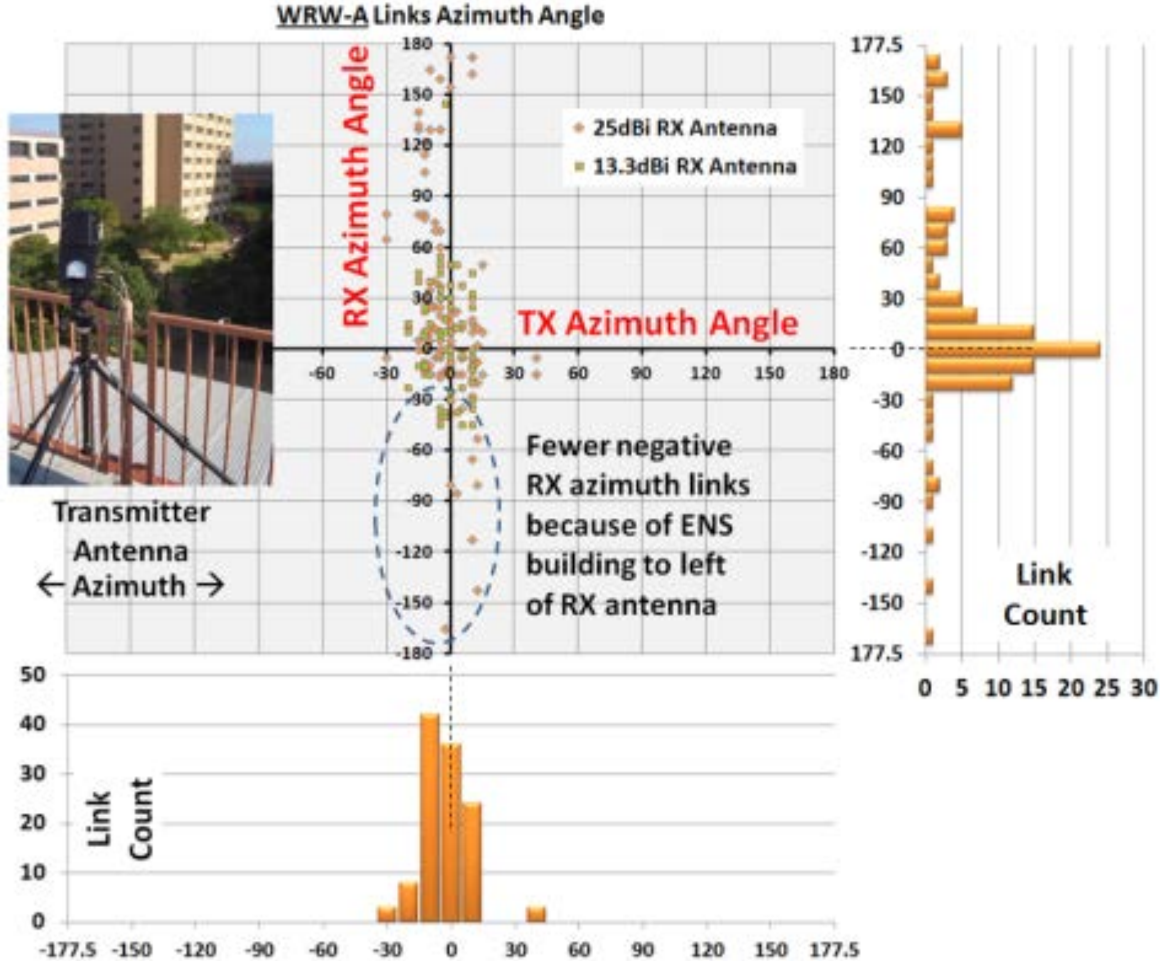





- Urban Streets
- Bus stops
- Over and under bridges
- Patios
- Building entrances
- Sidewalks
- Courtyards
- Parking lots
- Over concrete, asphalt, grass
- Scatterers:
  - Cars
  - Trees
  - Walls
  - Signs
  - Buildings (cement, brick, wood, glass, stone)
  - People

38 GHz Cellular AOA

TX height 23m above ground

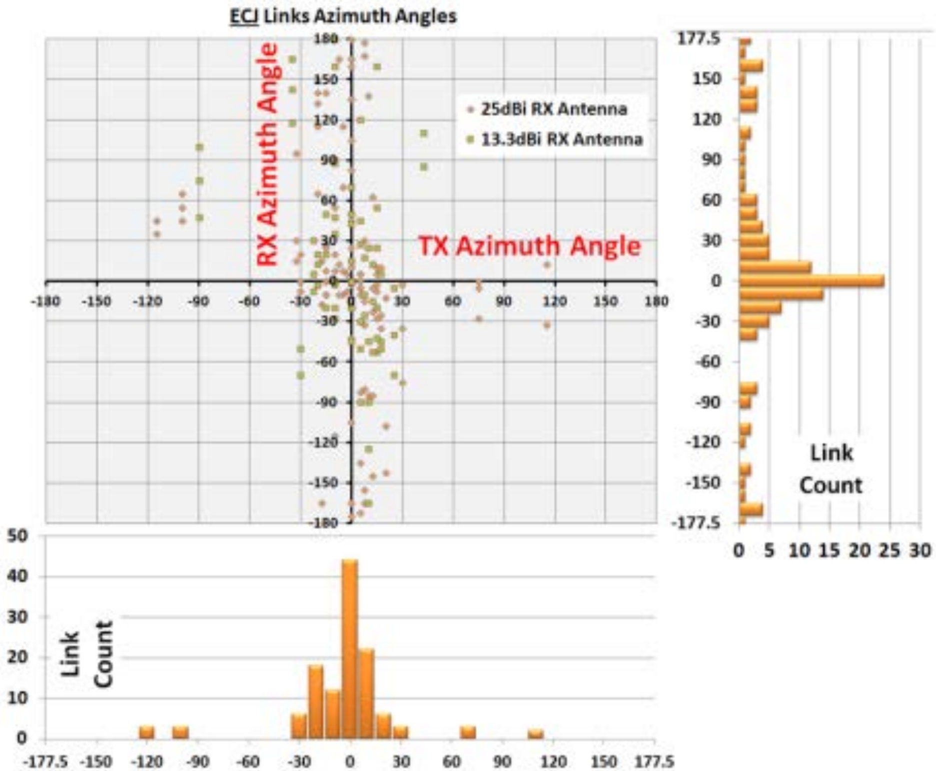


Histogram of RX angles for all links made using 25dBi antennas (10° bins)

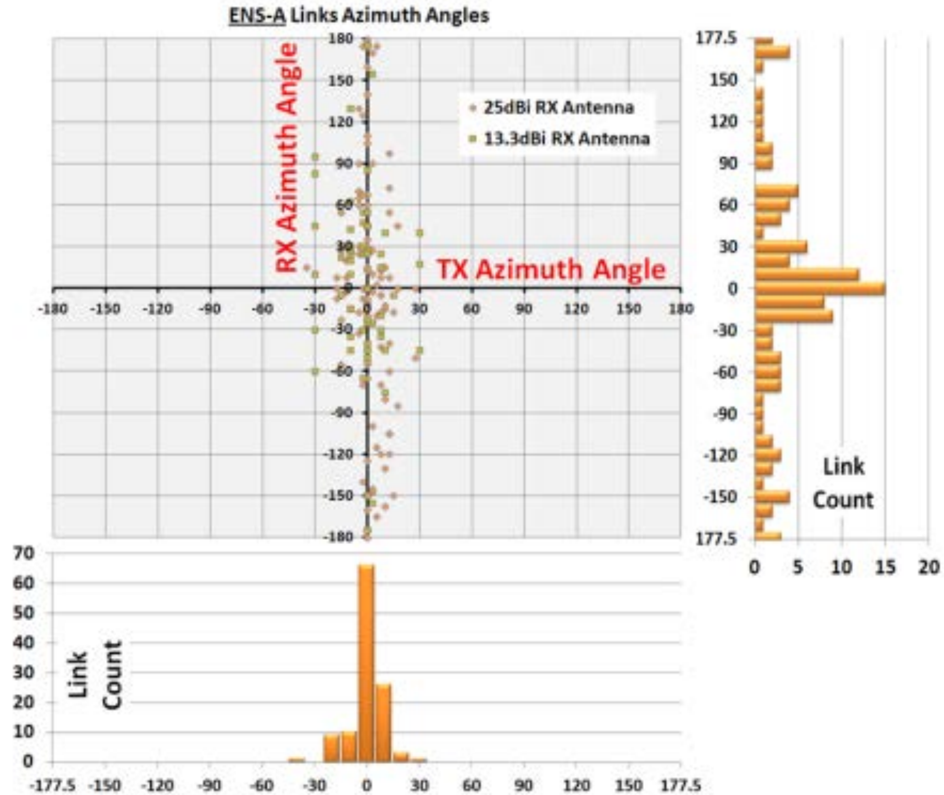
Histogram of TX angles for all links made using 25dBi antennas (10° bins)

38 GHz Cellular AOA

TX height 8m above ground



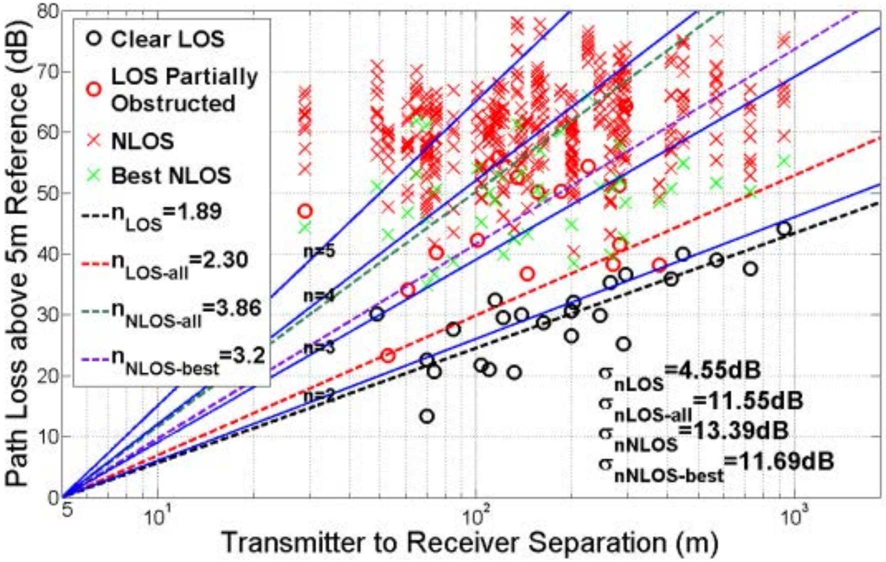
TX height 36m above ground



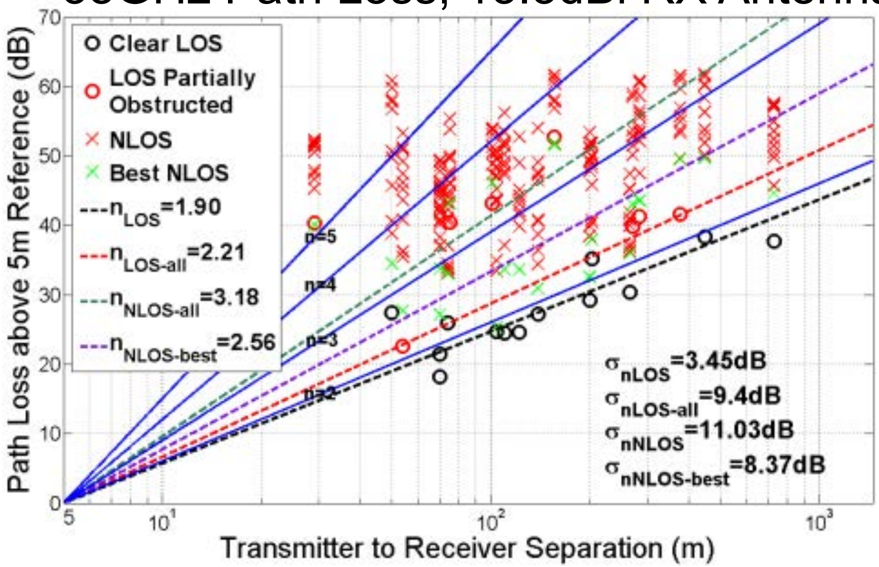
- TX angle spread is small but increases at low TX heights
- Receiver spread is heavily dependent on environment

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)

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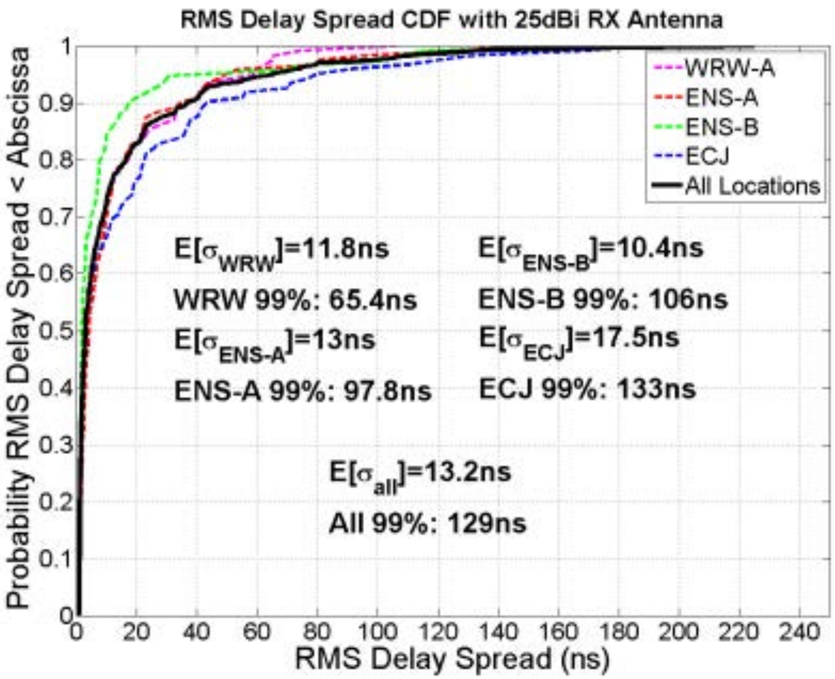
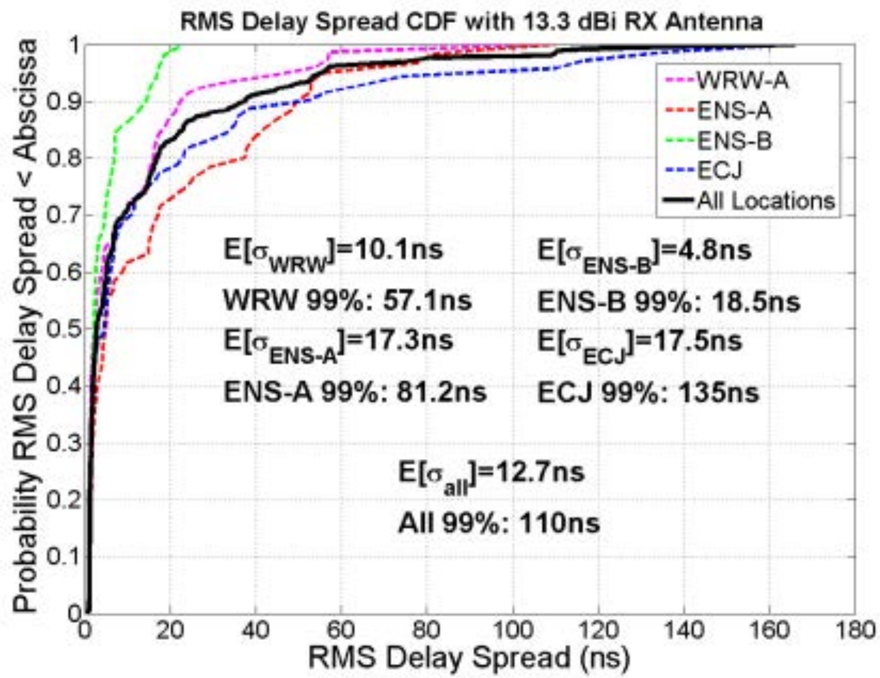
38 GHz Cellular RMS Delay Spread

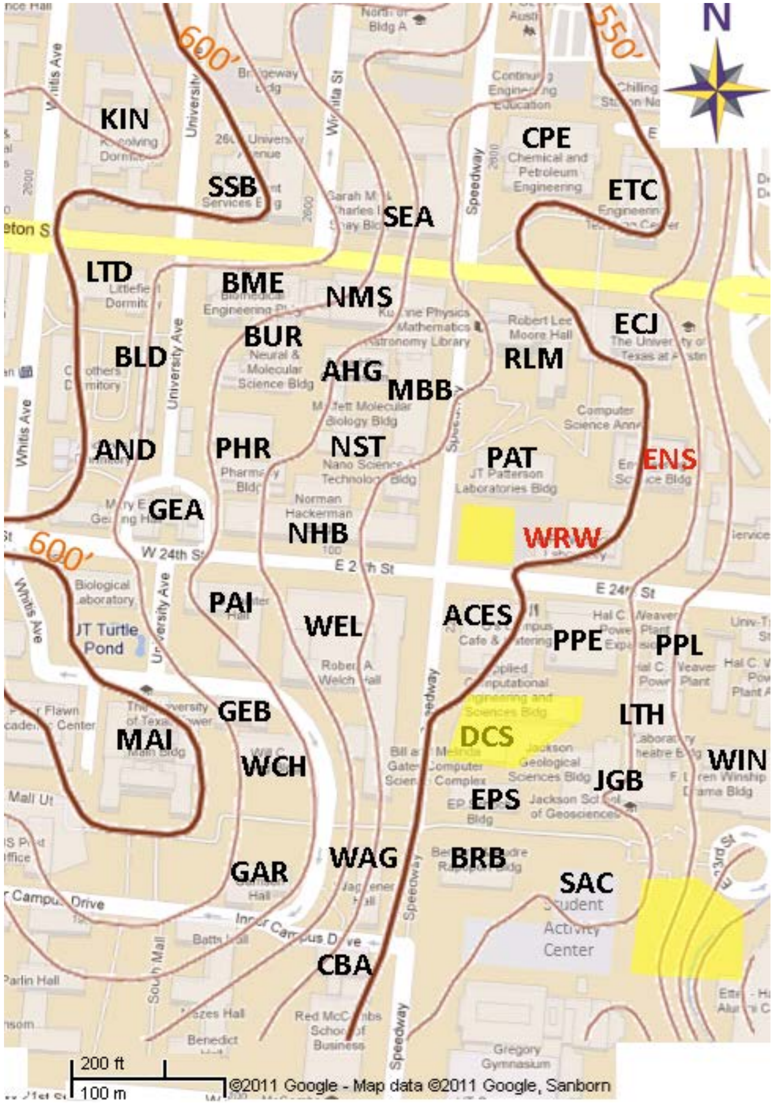
- RMS Delay Spread Cumulative Distribution Functions (CDFs) shown
- Using narrowbeam (25dBi) RX antenna, yields smaller variations between TX locations
- Total distributions are nearly the same for both 15 dB and 25 dB RX antennas





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



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.

Measuring New York City

NYU-Poly Brooklyn Campus

NEW YORK UNIVERSITY

Measuring New York City

The NYU Manhattan Campus

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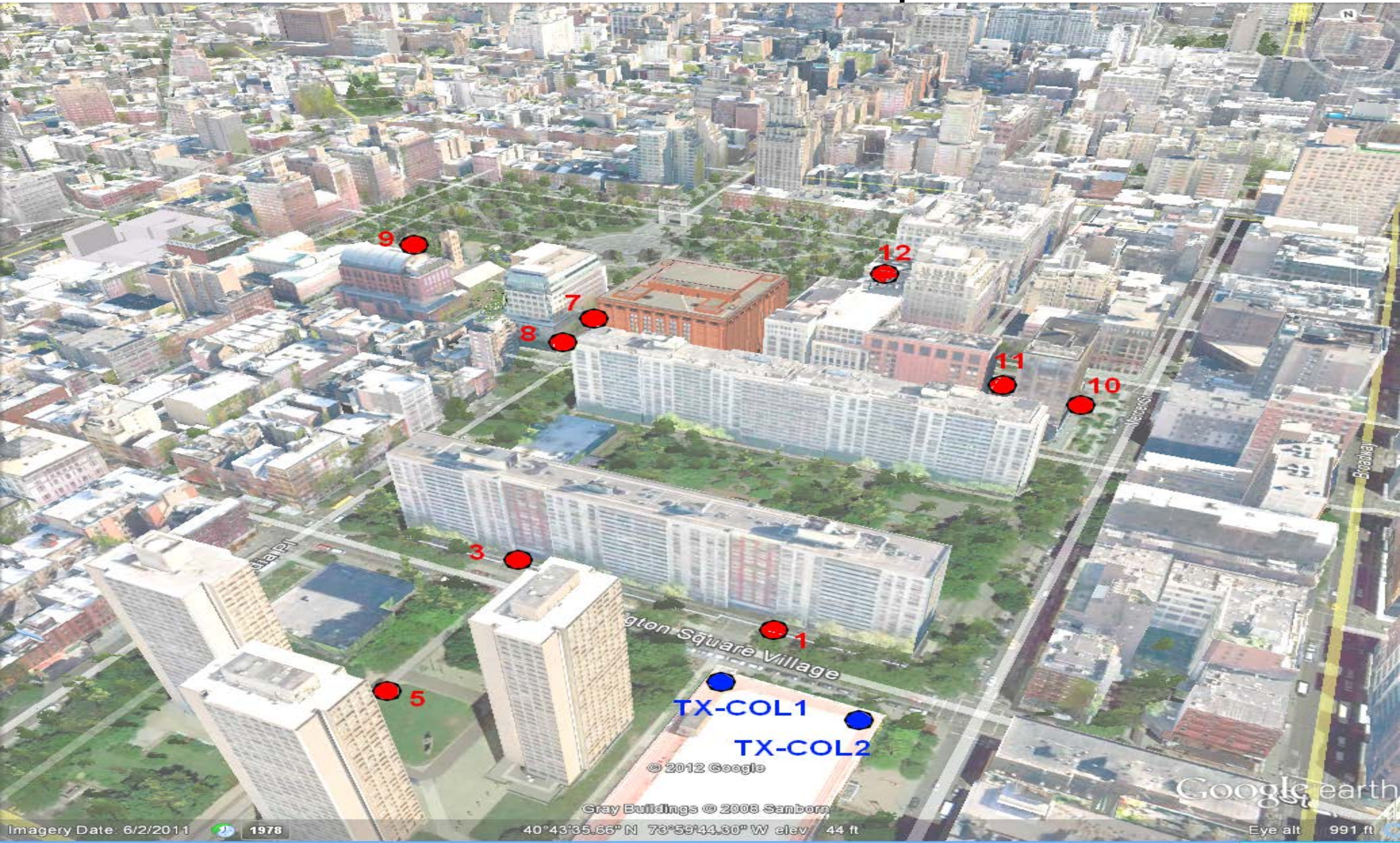


EPIC


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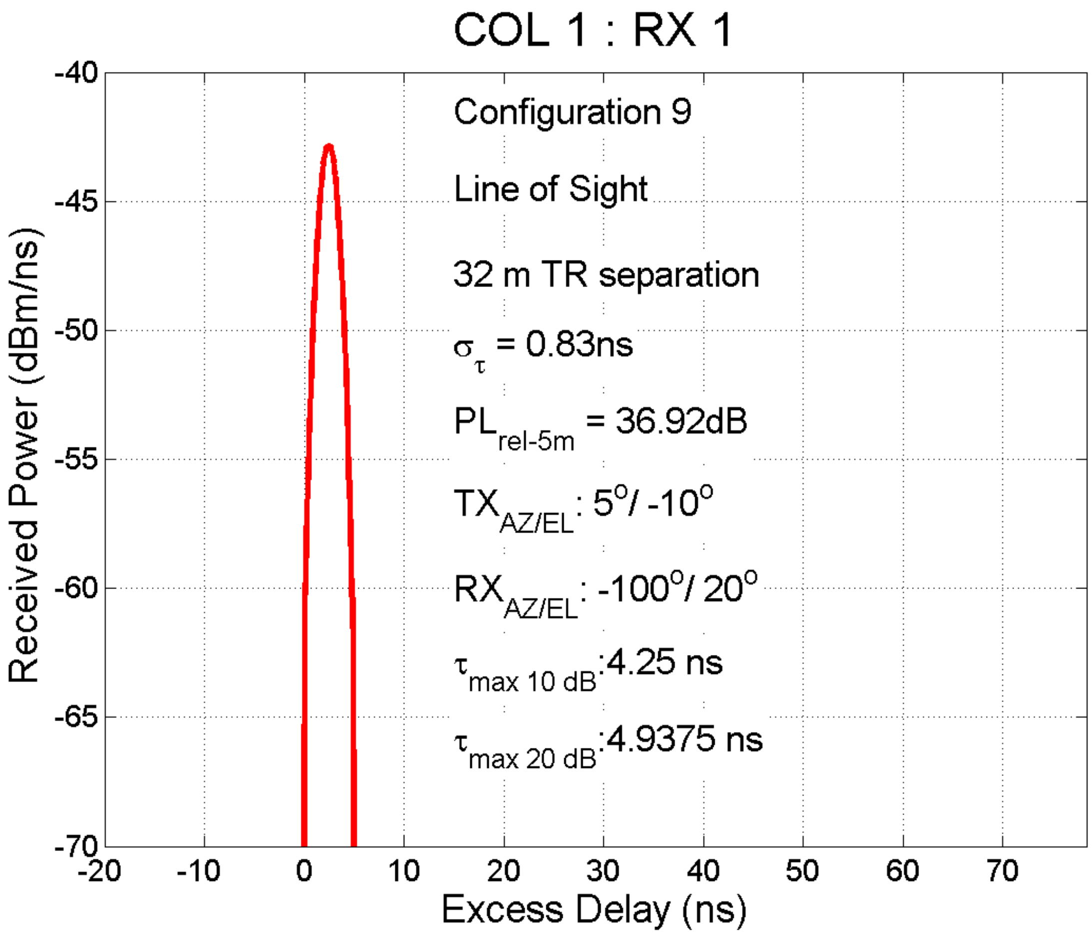
100


SUNDAY, JULY 1ST!
JULY 4th CELEBRATION
LOCATION TBD
FUERZA
BRUTA
Pi
SiGMA
Pi
Minority
Academic


TECH
207
FDNY
207
997347

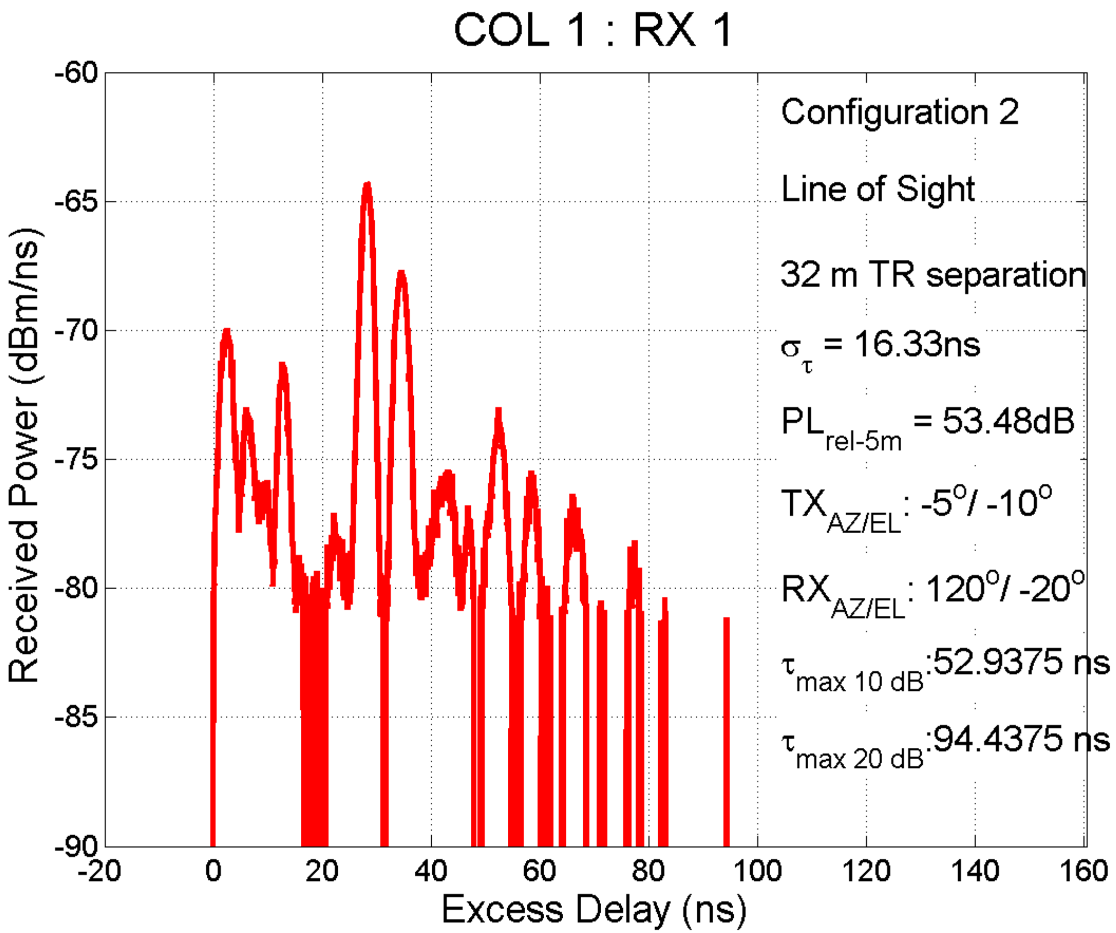
28 GHz LOS in Brooklyn



- TX and RX pointing directly at each other, each with 25 dB gain antennas

Manhattan measurement

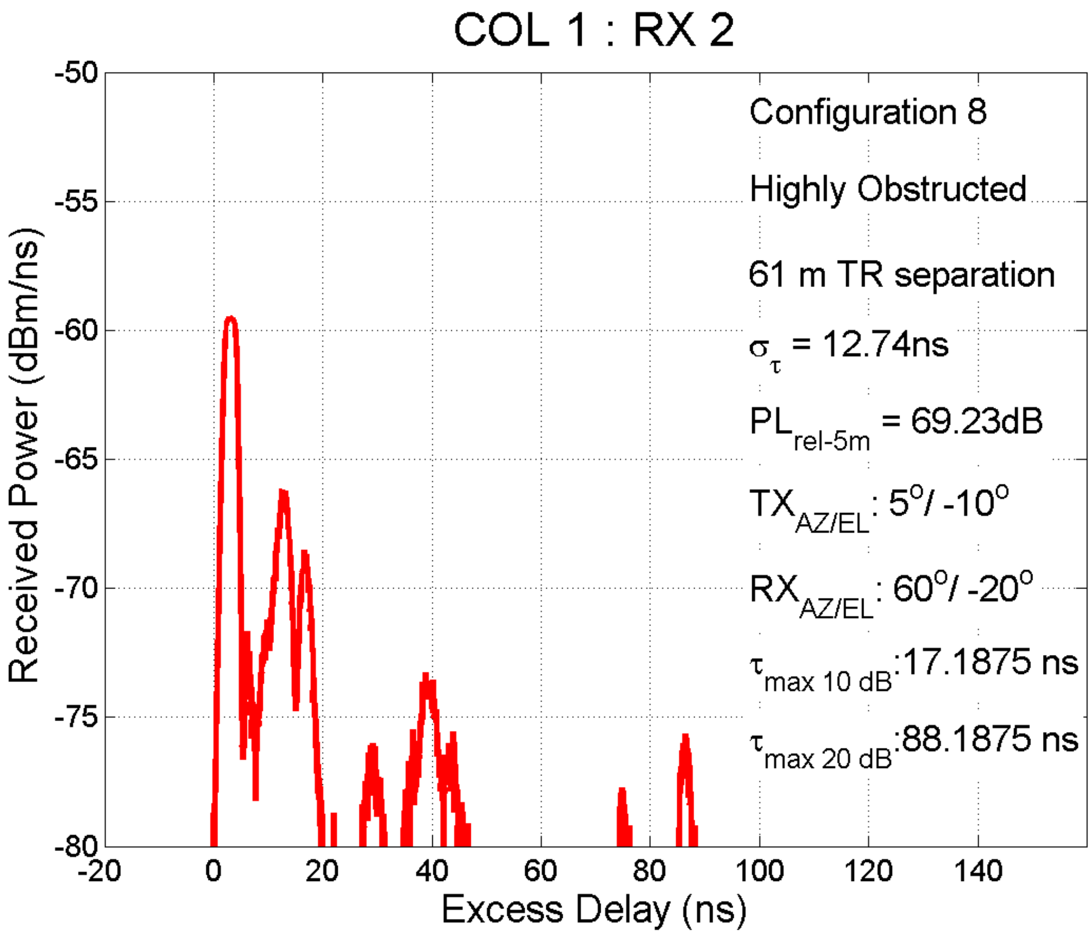
28 GHz LOS in Brooklyn



- Beamsteering is not on boresight at same location as previous slide
- RX pointing away from the TX towards a fence.
- TX pointing at RX

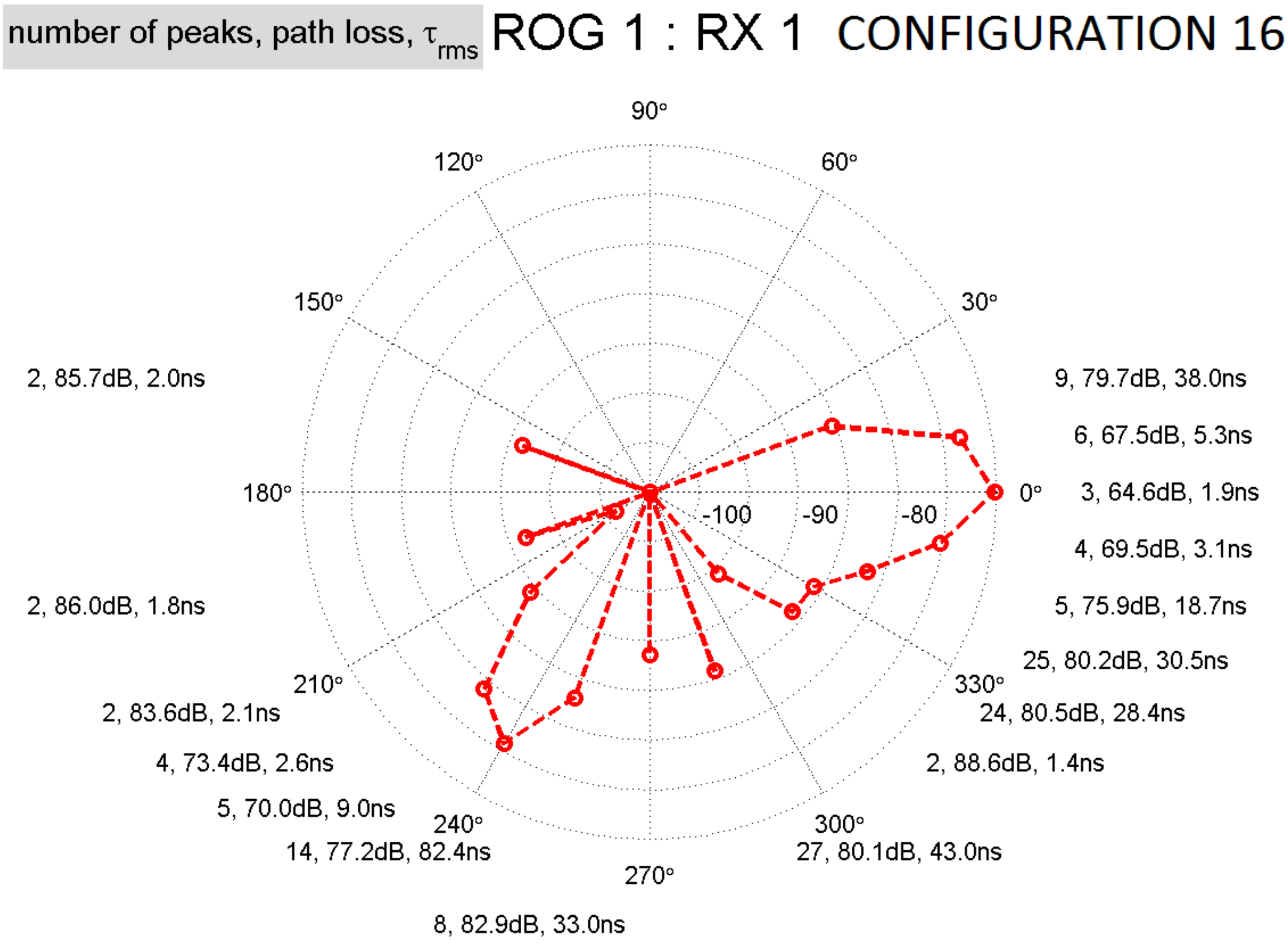
Manhattan measurement

28 GHz OBS location in NYC



- Diffraction study with 25 dBi antennas
- TX and RX pointing at a glass door of building

Partially Obstructed Polar Plot



- Signal was received in 16 different angles out of 36 (10 deg. res)
- Partially obstructed environment
- T-R separation – 135 meters
- Path loss values are relative to 5 meter free space (75.3 ± 1 dB)

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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 are currently investigating New York City
- On-chip and integrated package antennas at millimeter wave frequencies will enable massive data rates, far greater than today’s 4G LTE
- This an **exciting frontier** for the future of wireless

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Companies/Consortiums Developing mmWave Applications for WPAN

- Consortiums developing products – Wireless Gigabit Alliance (WiGig), WirelessHD
  - WirelessHD Alliance supports WirelessHD Standard
  - WiGig Supports WiGig Standard and IEEE 802.11ad

WiGig Wireless Gigabit Alliance — intel, DELL, SAMSUNG, MEDIATEK, Panasonic

WirelessHD — TOSHIBA Leading Innovation, SONY, BROADCOM, SiBEAM wireless beyond boundaries

- Companies developing products - NEC, Panasonic, LG, SiBeam, Sony, Intel, Broadcom, Toshiba, MediaTek, Samsung, and many more!
- WirelessHD , WiGig (now 802.11ad) products are now set for release

•J. Palenchar, "WirelessHD Group Cites Product Gains," TWICE: This week in Consumer Electronics, vol. 24, no. 19, September 21, 2009, pp. 30-30.
•J. Palenchar, "Next Generation of WirelessHD Gets CES Demo," TWICE: This Week in Consumer Electronics, vol. 25, no. 1, January 7, 2010, pp. 16 – 34.
• Wireless Giigabit Alliance, http://wirelessgigabitalliance.org/specifications/, accessed May 27, 2010

So…..how does Wireless Communications enter its Renaissance?

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NYU WIRELESS: Mission and Expertise

- **EXCITING NEW START UP**: 25 faculty and 100 students across NYU solving
problems for industry, creating research leaders, and developing fundamental knowledge and new applications using wireless technologies
  - NYU-Poly (Electrical and Computer engineering)
  - NYU Courant Institute (Computer Science)
  - NYU School of Medicine (Radiology)
- NYU WIRELESS faculty possess a diverse set of knowledge and expertise:
  - **Communications** (DSP, Networks, RF/Microwave, Chips)
  - **Medical applications** (Surgery, MRI, Compressed sensing)
  - **Computing** (Graphics, Data centers, Data mining, Algorithms)
- Current in-force funding:
  ~ $9 Million/annually from NSF, NIH, and Companies

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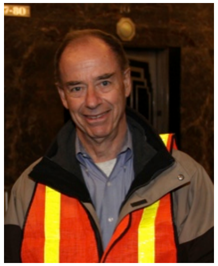
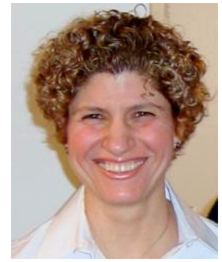
NYU WIRELESS Faculty

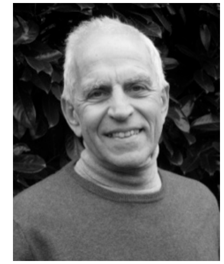

Henry Bertoni
Radio Channels
POLY


Ryan Brown
RF Coils/Imaging
NYUMC


Justin Cappos
Systems Security
POLY


Christopher Collins
MRI Imaging
NYUMC


Elza Erkip
Communications
POLY

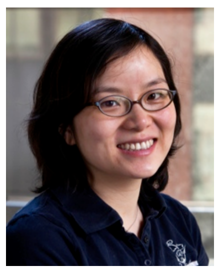

David Goodman
Communications
POLY

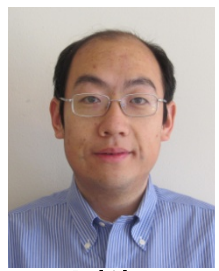

Mike Knox
RF/Microwaves
POLY

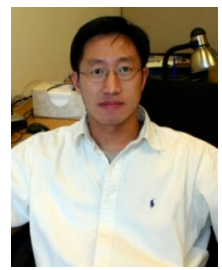

Marc Bloom
Anesthesiology
NYUMC


Ricardo Lattanzi
MRI Optimization
NYUMC

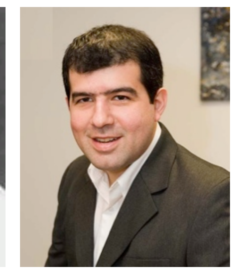

Daniel O'Neill
Anesthesiology
NYUMC


Jinyang Li
Networks
COURANT


Pei Liu
Wireless Networks
POLY


Yong Liu
Networks
POLY

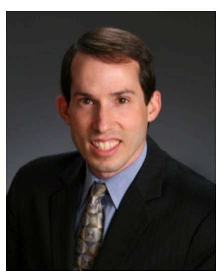

I-Tai Lu
Electromagnetics
POLY

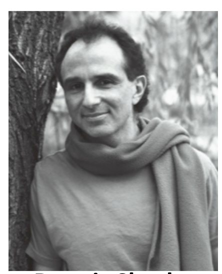

Ricardo Otazo
MRI Imaging
NYUMC


Shivendra Panwar
Cross-layer Design
POLY


Sundeep Rangan
Communications
POLY


Ted Rappaport
Communications
POLY


Dan Sodickson
RF/ MRI Design
NYUMC


Dennis Shasha
Algorithms/Data
COURANT


Lakshmi
Subramanian
Computing
COURANT


Jonathan Viventi
Medical Electronic
POLY


Peter Voltz
DSP/Comms.
POLY


Yao Wang
Image/Video
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NYU WIRELESS Industrial Affiliates

NATIONAL INSTRUMENTS™

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INTERDIGITAL®

L3

About NYU

New York University

- The largest and oldest private universities in the USA (1831)
- Origins in Telecom: Samuel Morse (Morse Code) first faculty member
- Pioneering the Global Network University w/campuses in Abu Dhabi, Shanghai, Toronto, Buenos Aires, and 18 other countries
- Faculty have received 34 Nobel Prizes, 16 Pulitzer Prizes, 21 Academy Awards, 10 National of Science Medals
- New focus in Engineering for the Urban, Telecom, Bio-Med future
- NYU is ranked #33 in 2012 USNWR National University Ranking
  - (GA Tech is 36, UT Austin is 45)

Wireless, Computing, and Medicine

The Annual International Conference of Cardiology

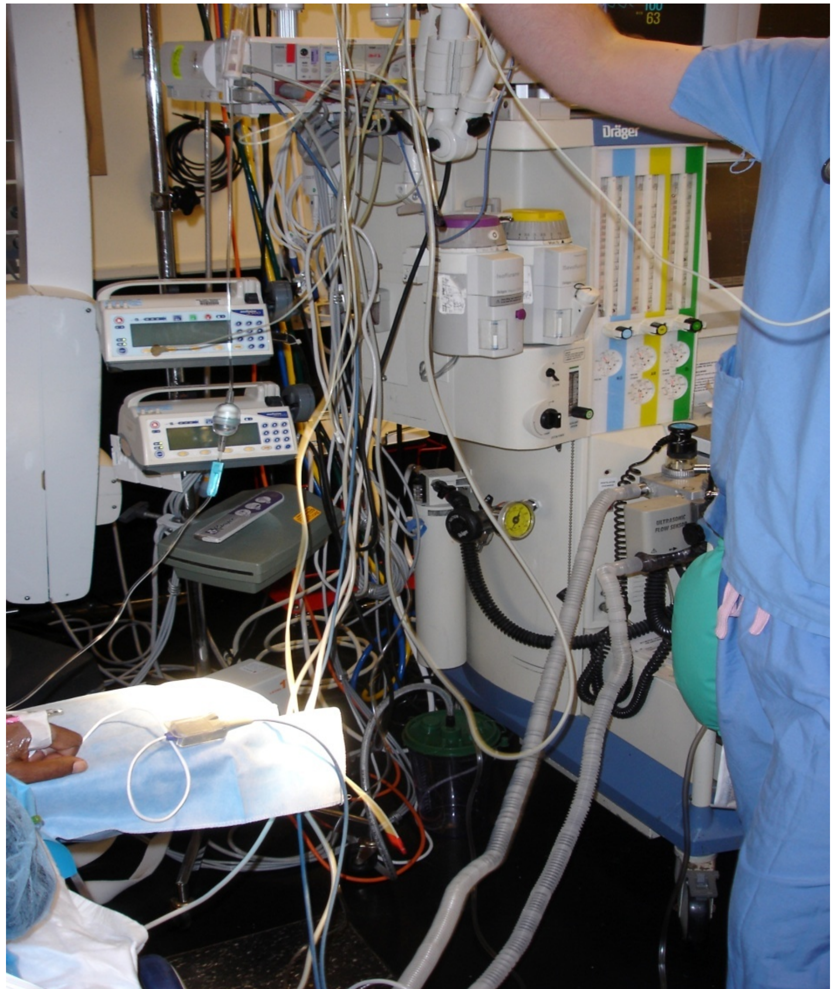
Theme: Linking Scientists, Engineers and Physicians

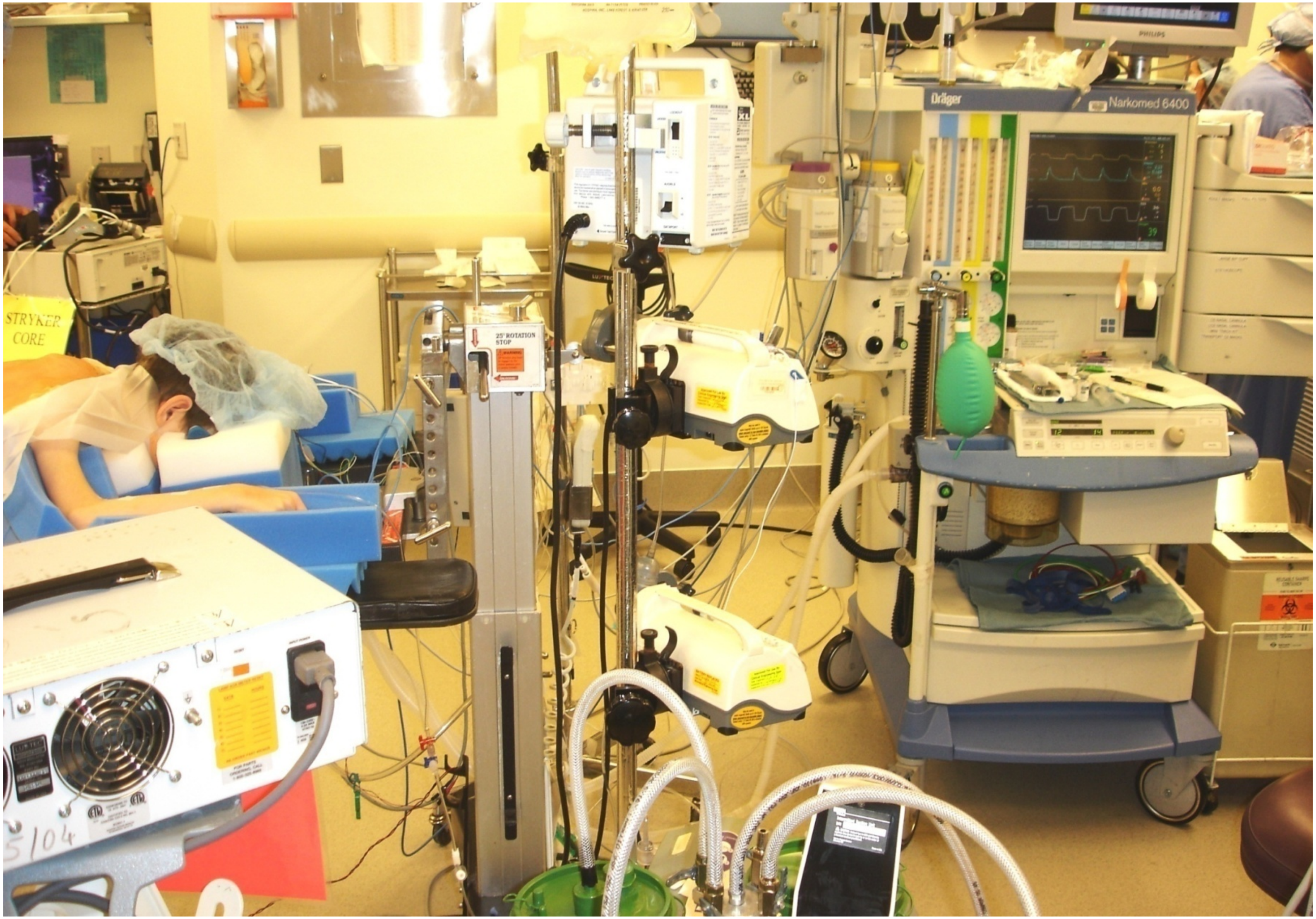
December 2-4, 2012

Guangzhou Baiyun International Convention Center

CHINA

Why Wireless and Medicine?




STRYKER
CORE
25° ROTATION
STOP
Dräger
Narkomed 6400
PHILIPS

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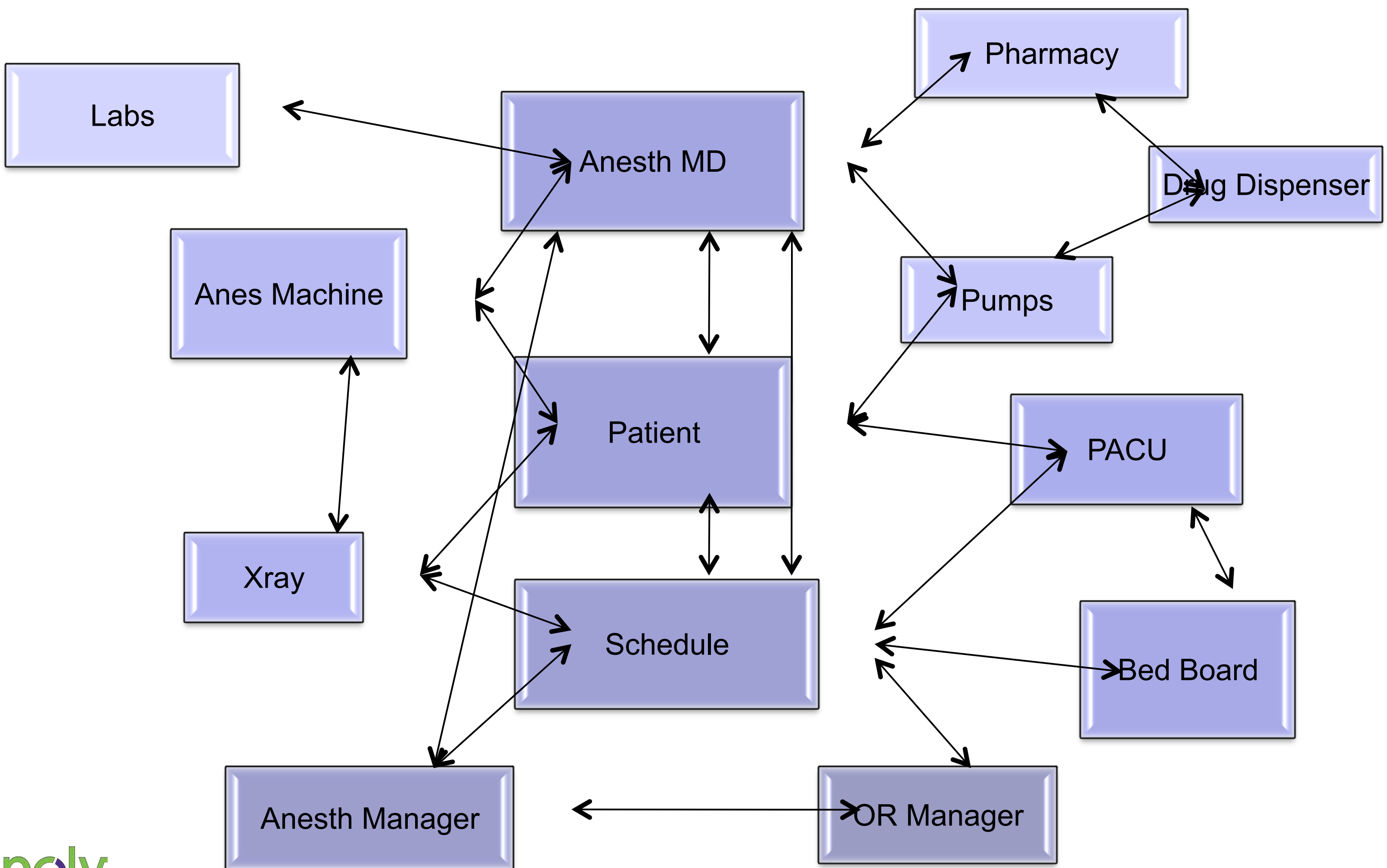
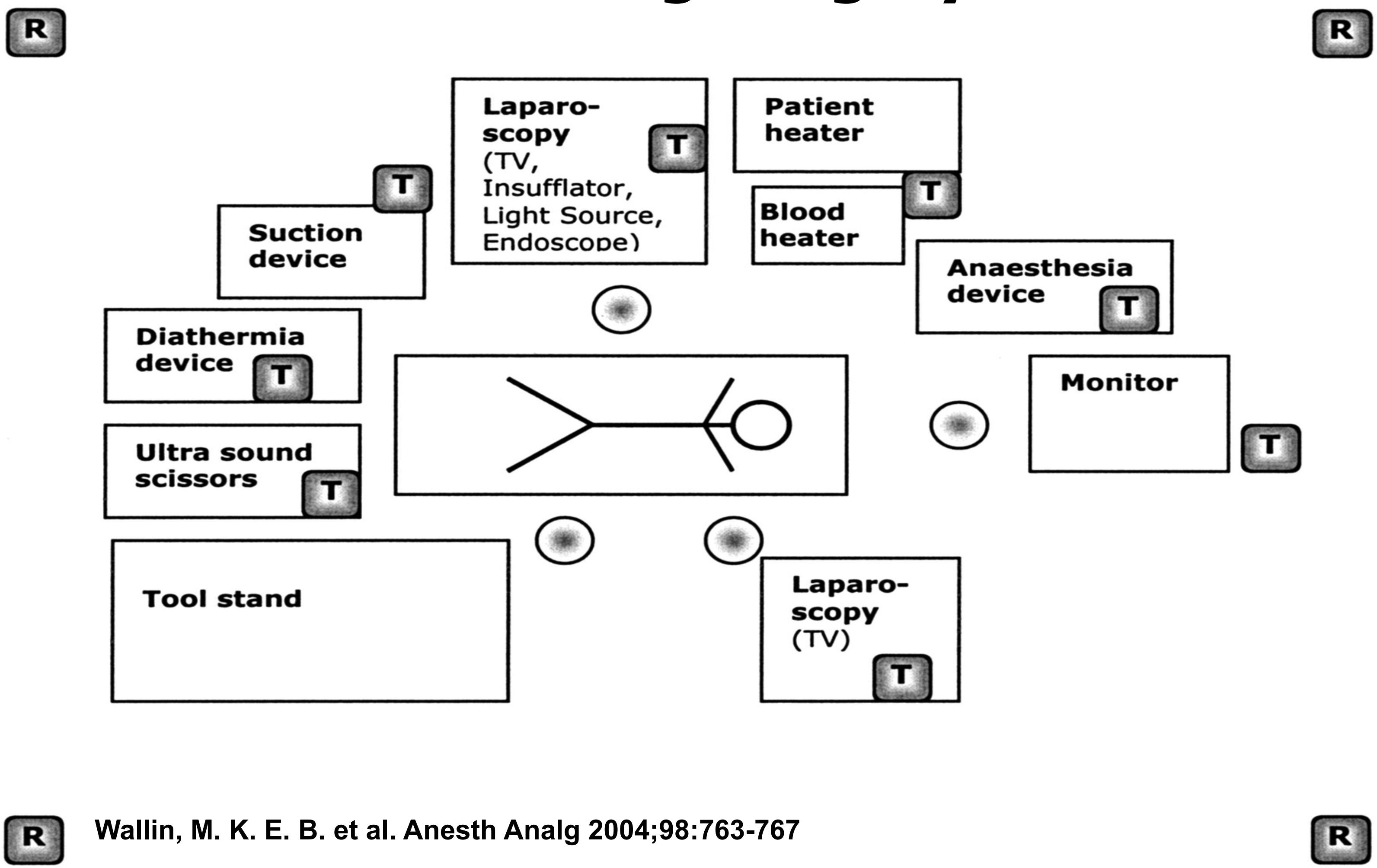
The Problems

- Many independent devices
- Massive disparate non-standard data
- Potential for RFI and Ground loops
- Lack of interconnectivity
- Tethering
- Trip hazards

In Anesthesia – Interconnectivity is Key



Clinical Tests Conducted During Surgery



Wallin, M. K. E. B. et al. Anesth Analg 2004;98:763-767

Anesthesiologists Can Improve Patient Satisfaction

- Analgesia
- Amnesia
- Empathy
- Safety

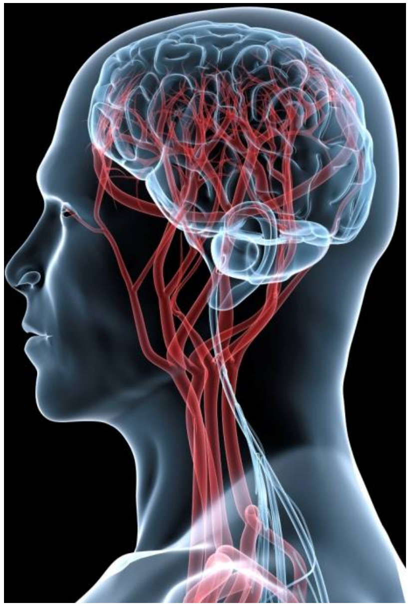
Cardiologist Doing Procedure Can *Focus* on Cardiac Electrophysiology

- Improved Efficiency
- Fewer Complications
- Better Outcomes
- Less Aggravation

Possible Interventions in ICU/OR

- **Increase arterial oxygen content:**
  - Transfuse red blood cells (↑Hb or hematocrit)
  - ↑ arterial partial pressure of oxygen (↑FiO_2)
- **Increase cerebral blood flow:**
  - ↑ cardiac output (HR x stroke volume, SV)
  - ↑ SV w/fluids and medications
  - ↑ BP by heart contractility & systemic vascular resistance
  - ↑ arterial partial pressure of carbon dioxide (↑$PaCO_2$)
- **Reduce cerebral metabolic rate:**
  - Controlled hyperthermia
  - Sedation
- **Reduce cranial pressure:**
  - ↓ central venous pressure

Why Cerebral Oximetry?



- The brain:
  - Complex and fragile system
  - Typically needs ~15% of normal cardiac output
  - Consumes ~20% of all oxygen used by the body
  - Elapsed time critical in desaturation events
- The need is critical:
  - Cerebral Ischemia: the leading cause of compromised neurocognitive outcomes
  - The duration of reduced oxygenation has a direct impact on brain function

Cardiac Electrophysiology

- Clinical Cardiac Electrophysiology (aka: “EP”) is a sub-specialty of cardiology
- It is the study and treatment of cardiac arrhythmias
- The practice of EP is performed in the EP Laboratory, a dedicated area combining aspects of a traditional operating room, radiology, and signal processing equipment
- Both diagnostic and therapeutic (curative) procedures are performed

Cardiac Electrophysiology

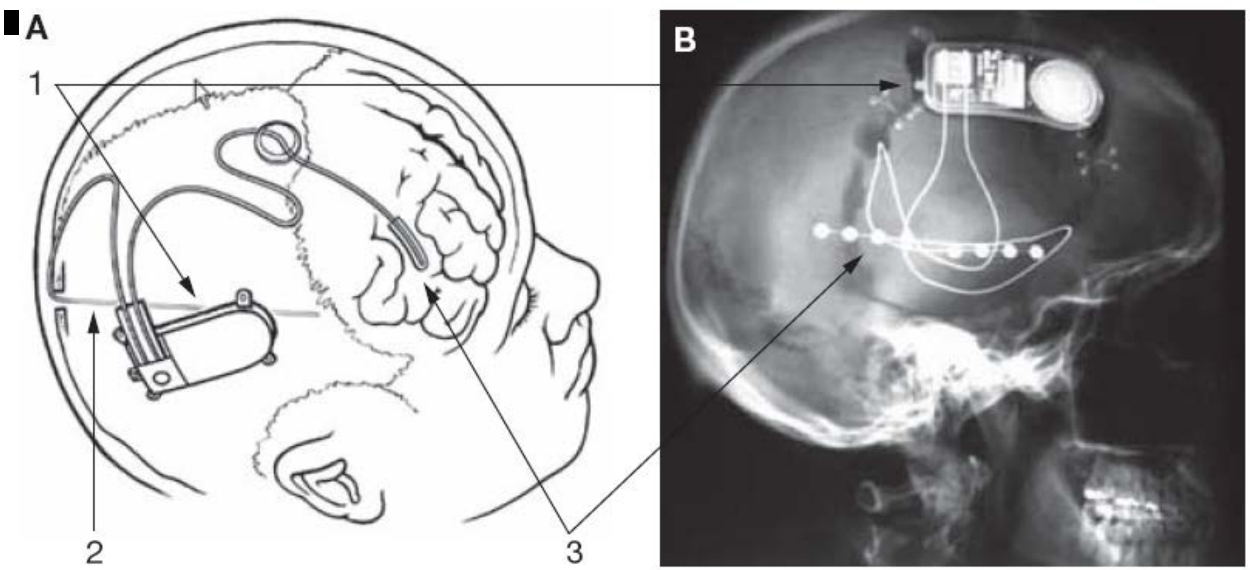
- EP is very technology-intensive
- A broad range of signal processing and imaging equipment is required for even the most basic EP procedure
- The “wireless revolution” has not yet hit the EP lab
- The EP physician has historically functioned as the hardware interface between the various equipment required
- This has become increasingly complex as technology has advanced to the point where EPs are now able to cure arrhythmias previously deemed incurable

Cardiac EP

- Despite recent advances in technology and success in catheter ablation techniques, many vexing problems remain. Doctors need:
- Wireless connectivity within the EP lab
- Universal user interface among various technologies
- Improved temporal and spatial resolution of mapping techniques
- Improved accuracy and efficacy of lesion delivery

Implantable Devices for Medicine

- Implantable devices have evolved



NeuroPace Responsive Neurostimulator (RNS®)

Vagus Nerve Stimulator
Cyberonics, Inc.

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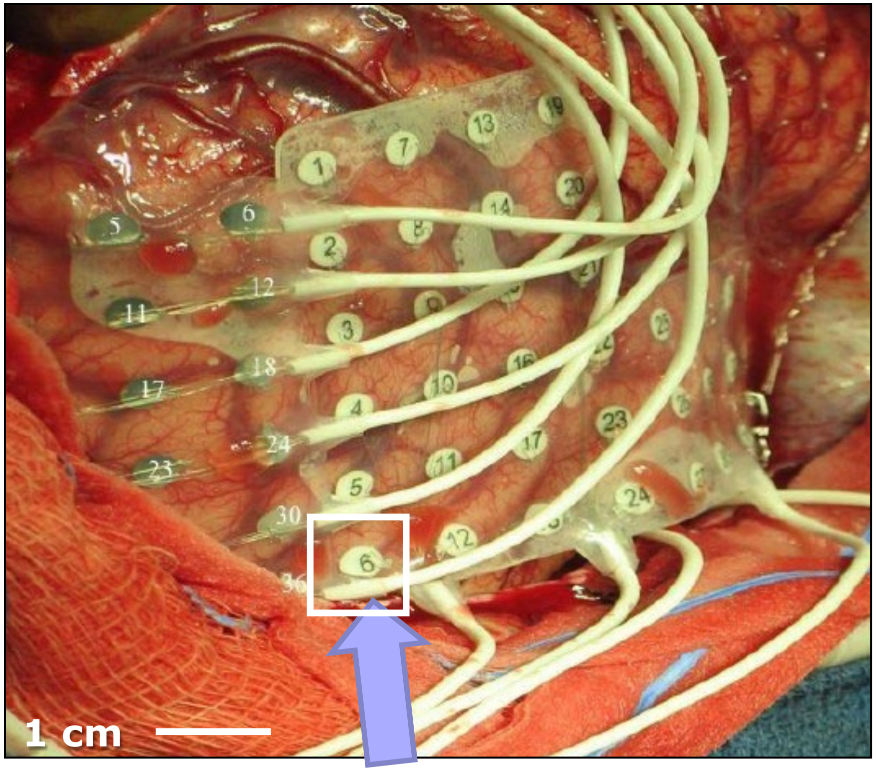
"State of the Art" Clinical Electrode Arrays



12 Million Neurons → 1 Electrode

- Large contacts
- Spaced 1 cm apart
- 1 Electrode interfaces with ~12M neurons!
- Very poor spatial resolution
- Need 1,000s of electrodes, but not 1,000s of wires

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Flexible Silicon Electronics to Improve Electrode Arrays in the Body

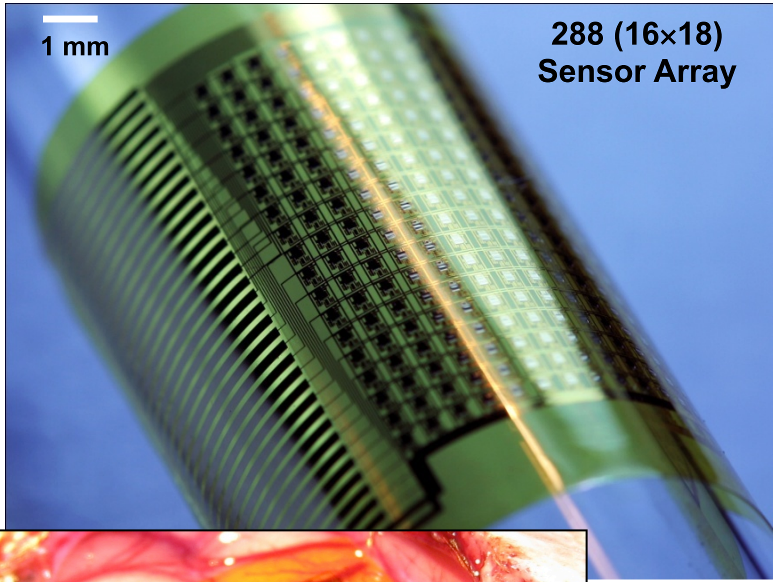
Conformal to Brain
- 25 μm thickness
- 2.8 μm using biodegradable silk

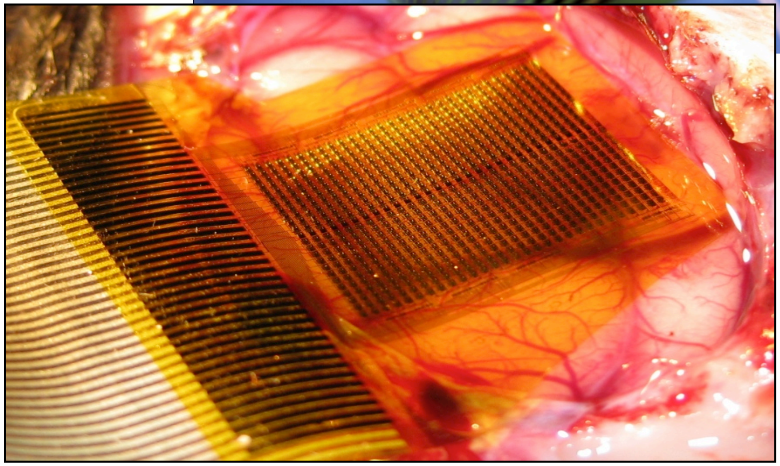
High spatial resolution
- **1024 <u>Active</u>** Electrodes
- 250 μm spacing

High temporal resolution
- Up to 12.5 kHz sampling

Multiplexing & Amplification
- ***~40 wires***
- Amplifier at each electrode

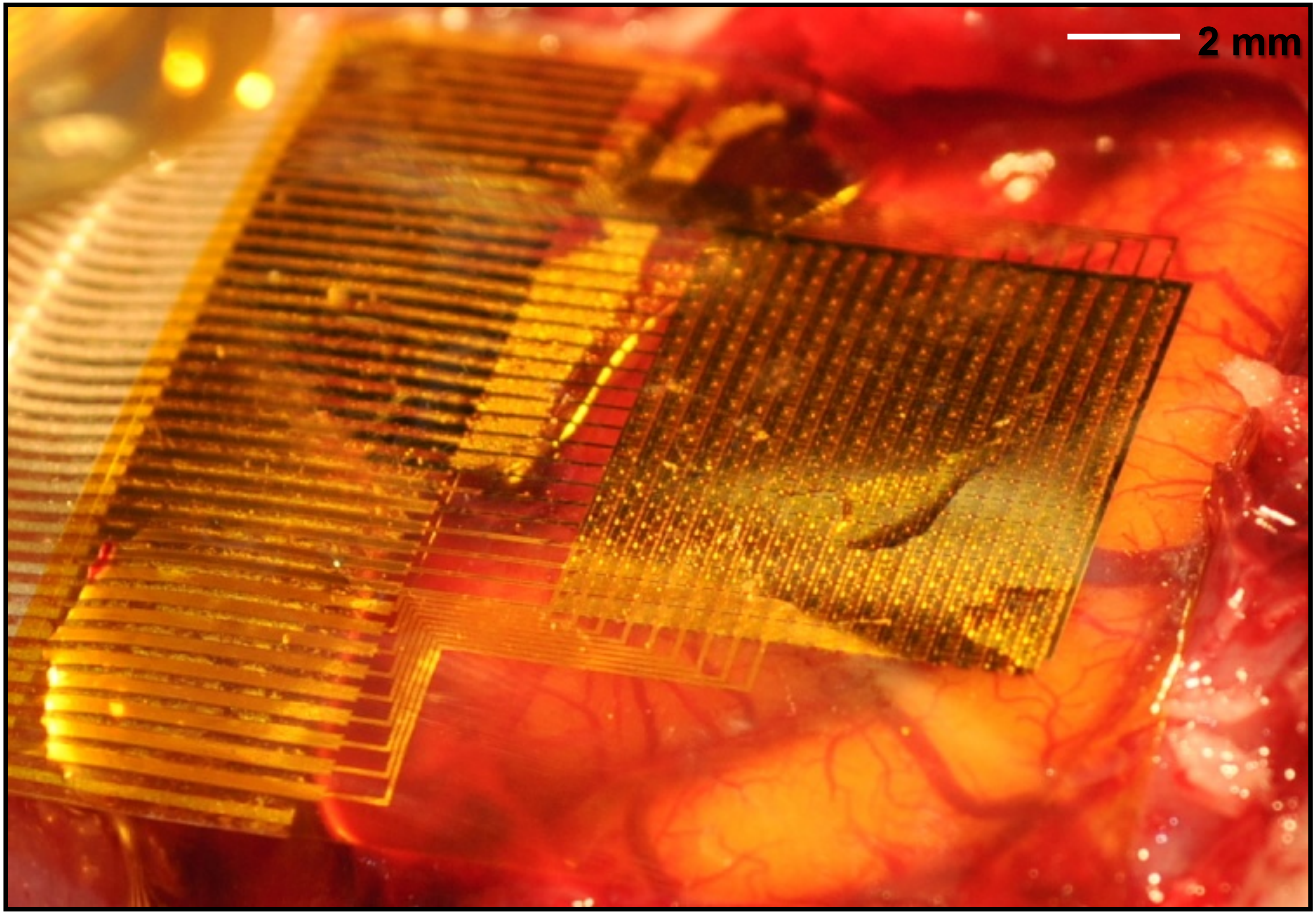
Scalable
- 1000s of electrodes
- Fewer wires





Viventi, J., Kim, D-H. et al. *Science Translational Medicine* **2**, 24ra22 (2010).

Electrode on Brain



Viventi, J., Kim, D-H. et al. *Nature Neuroscience, In Press*

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, 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 medicine and the hospital of the future

NEW YORK UNIVERSITY

Recent Publications related to this Work

T.S. Rappaport, J.N.Murdock, F. Gutierrez, Jr., "State-of-the-art in 60 GHz Integrated Circuits and Systems for Wireless Communications," *Proceedings of the IEEE*,, August 2011, Vol. 99, No. 8, pp 1390-1436.

F. Gutierrez, S. Agarwal, K. Parrish, T. S. Rappaport, "On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems," *IEEE Journal on Selected Areas in Communications*, Vol. 27, Issue 8, October 2009, pp. 1367-1378.

F. Gutierrez, T. S. Rappaport, J. Murdock, "Millimeter-wave CMOS On-Chip Antennas for Vehicular Electronic Applications," *IEEE Vehicular Technology Conference (VTC)*, Ottawa, Canada, September 6-9, 2010, 5 pp.

J. Murdock, E. Ben-Dor, F. Gutierrez, T.S. Rappaport, "Challenges and approaches to on-chip millimeter wave antenna pattern measurements," IEEE Microwave Symposium Digest (MTT), Baltimore, MD, June 5, 2011

T. S. Rappaport, E. Ben-Dor, J. N. Murdock, Y. Qiao, "38 GHz and 60 GHz Angle-Dependent Propagation for Cellular & Peer-to-Peer Wireless Communications,“ IEEE International Conference on Communications (ICC 2012), June 2012.

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