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The Coming Renaissance of the Wireless Communications Age

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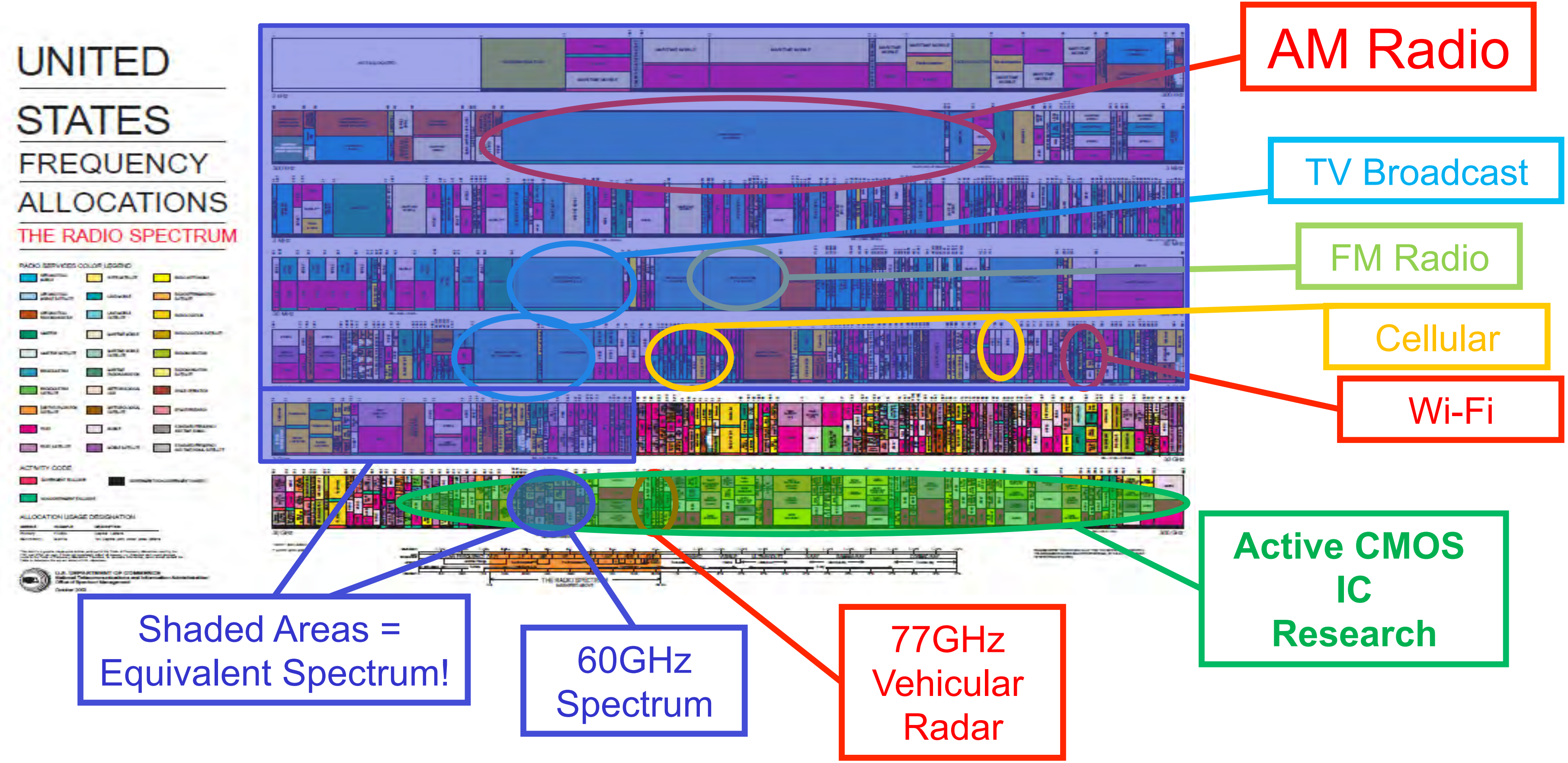
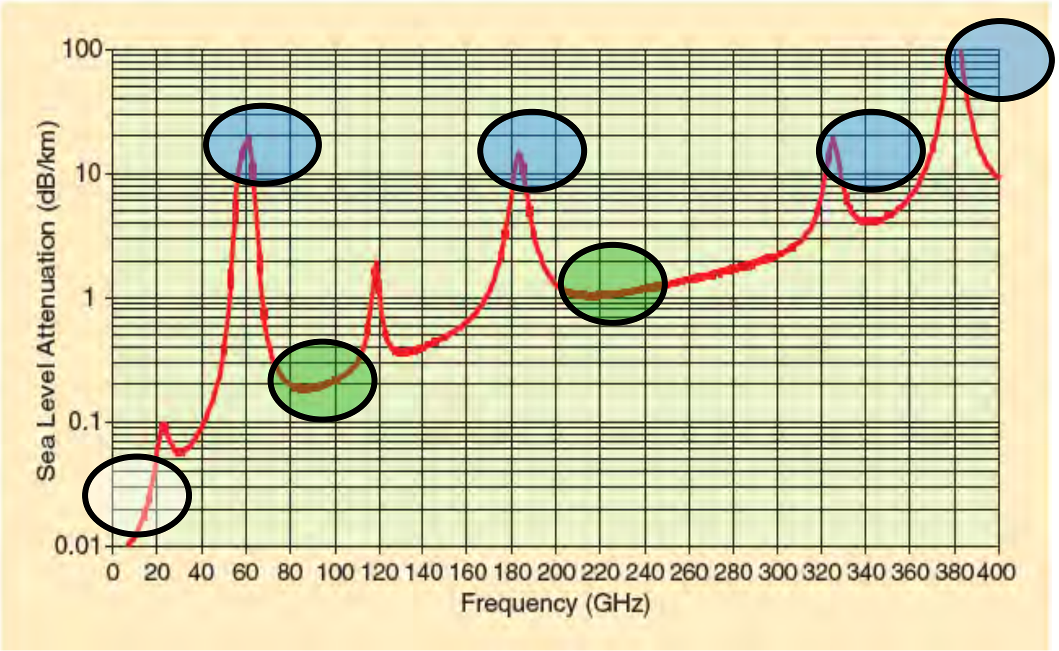
NYS Wireless Association Meeting
New York, NY
May 1, 2014

Spectrum = real estate



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

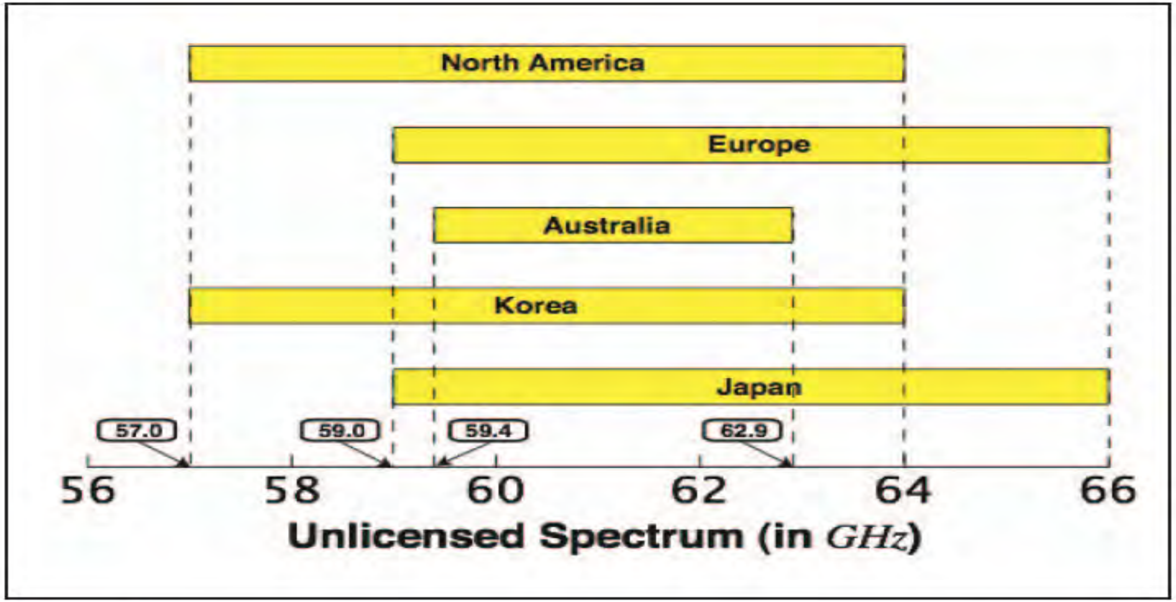
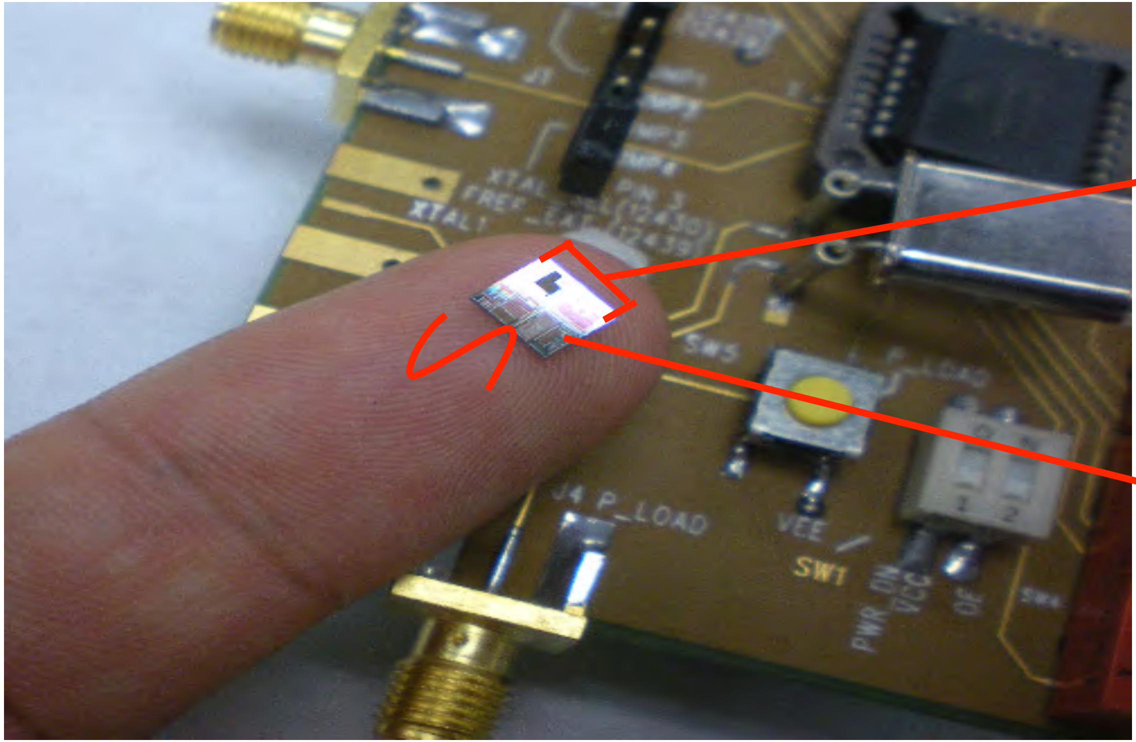


FIGURE 1 International unlicensed spectrum around 60 GHz.

- 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

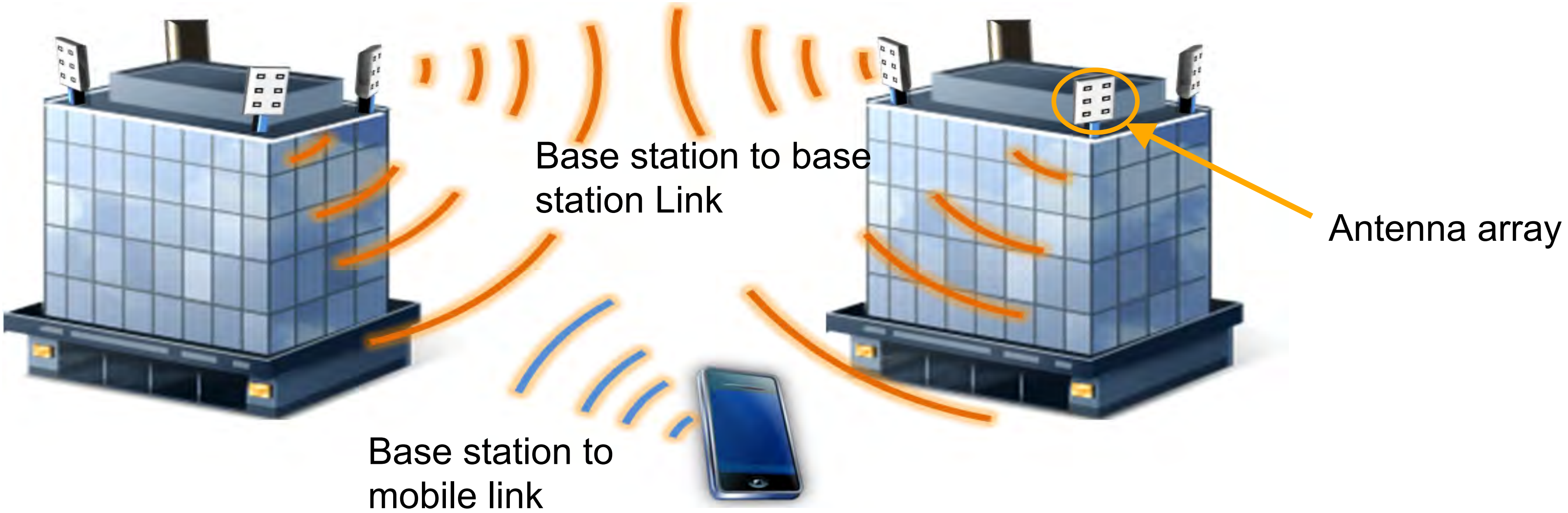
Cellular and Wireless Backhaul

Trends:

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

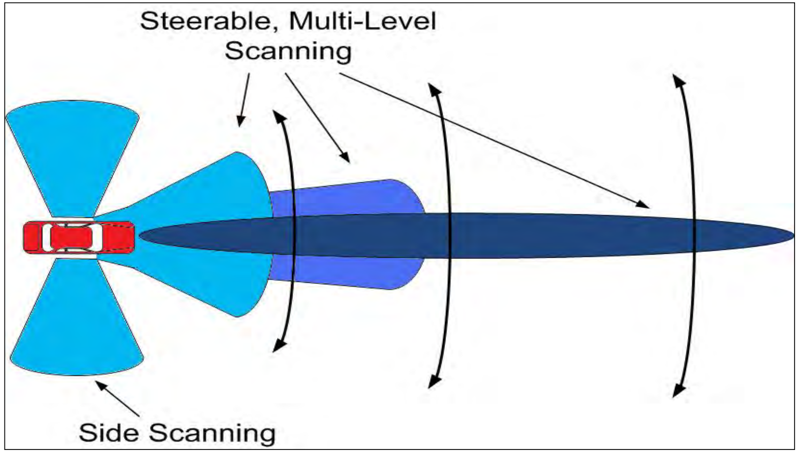
Problem: fiber optic backhaul is expensive and difficult to install.

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



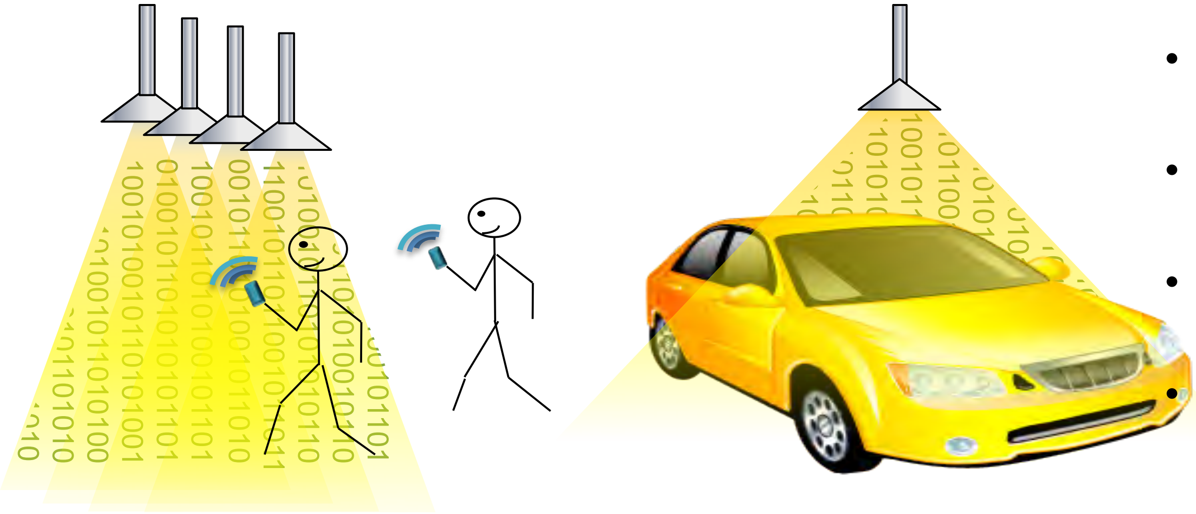
Mobile & Vehicle Connectivity

- 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

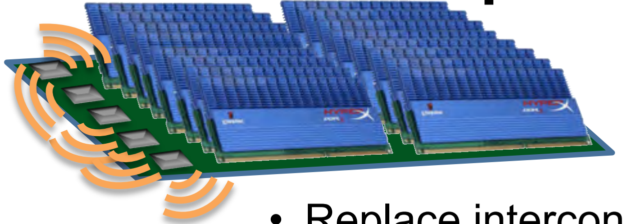


- The future: Showering of information
- Mounted on ceilings, walls, doorways, roadside
- Massive data streaming while walking or driving
- Roadside markers can provide safety information, navigation, or even advertisements

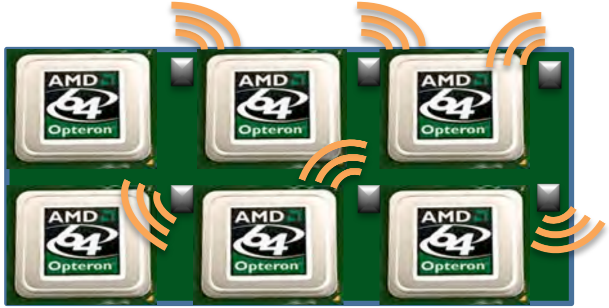
Gutierrez, F.; Rappaport, T.S.; Murdock, J. " Millimeter-wave CMOS On-Chip Antennas for Vehicular Electronic Applications," *72nd IEEE Vehicular Technology Conference Fall 2010.*

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," Delivered by T. S. Rappaport, Wireless at Virginia Tech Symposium, Blacksburg Virginia, June 3-5, 2009.

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

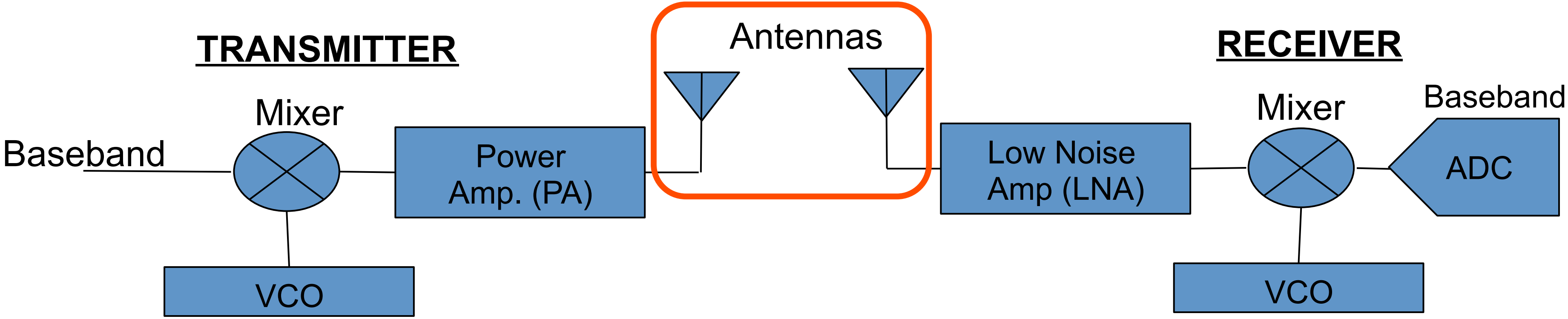
- A **wired** 10 meter link in a data center requires ~ 1 W of power
- Compare a **wireless** 60GHz link – **more flexible, less cost, same power**

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.

On-Chip Antennas for mmWave

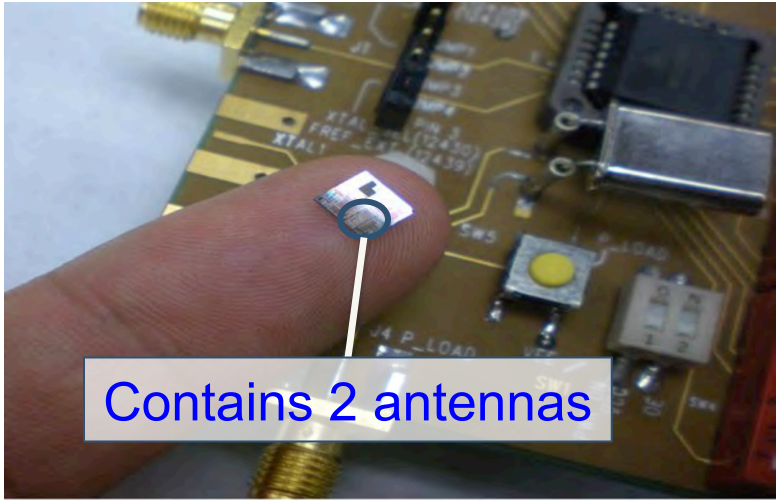


- Motivation
- Challenges of On-Chip Antennas: Radiation into Substrate, Need for Material Parameters
- Different Antenna Topologies
- On-Chip Optimization: Dipole and Yagi Placement, Rhombic Arm Angle and Thickness
- Overcoming On-Chip Challenges: Techniques to Improve On-Chip Gain and Efficiency

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

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



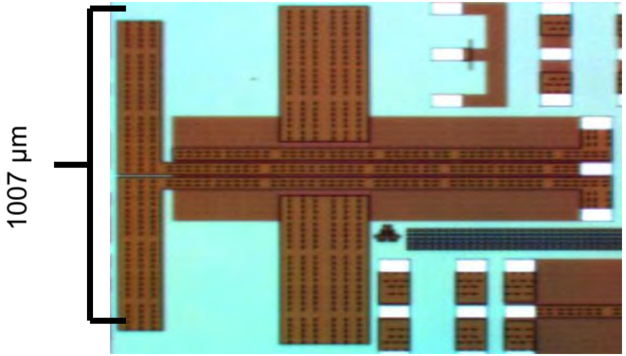
- Antenna sizes are comparable to integrated circuit (IC) sizes
- Tiny metal sheets available on ICs
  - Can be used to fabricate mmWave/THz antennas
  - Enough IC area available for directional arrays
- Saves PCB real estate
  - (ex: handhelds, laptops, etc.)
- **Reduces fabrication costs**
- Pushes 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.

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



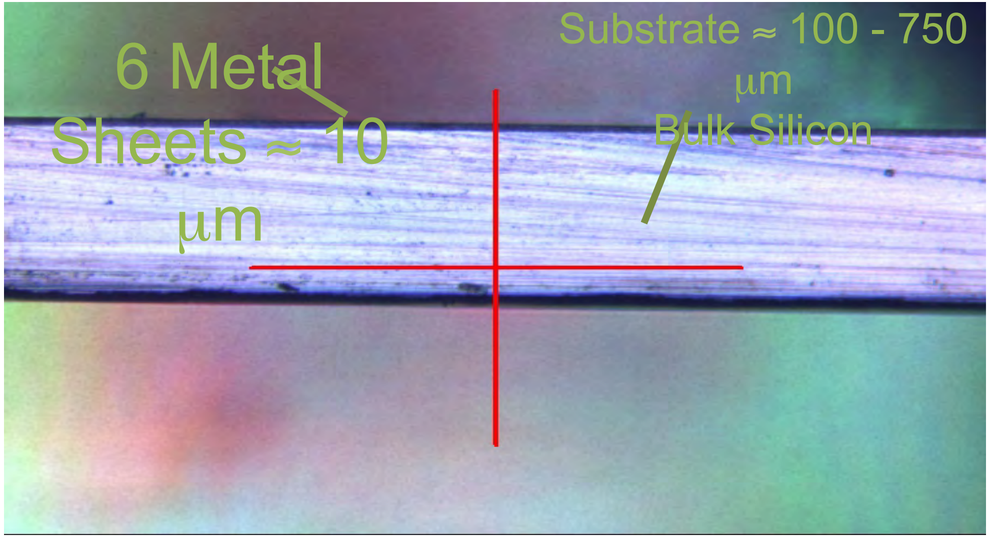
- Beamforming has been introduced into mmWave standards (e.g. IEEE 802.11ad)[1]
- Beam steering can be used to create a non-LOS link by reflecting off objects in the environment.

[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.

Substrate Radiation and Process

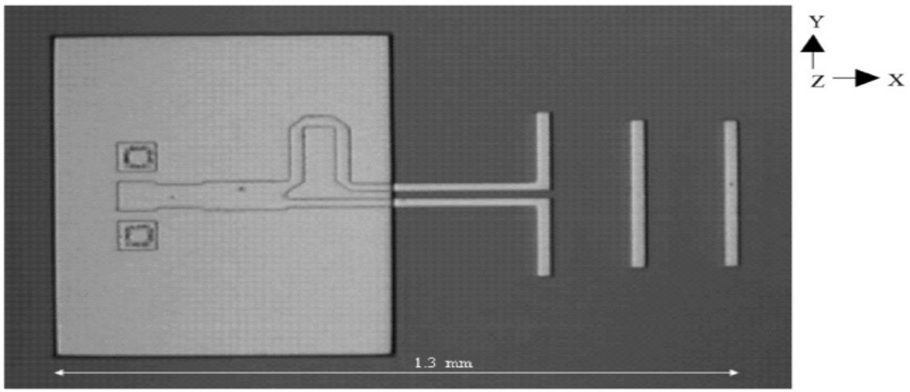
- New generations of CMOS = Higher doping concentration
  (less resistance to avoid latch up = turning on of parasitic BJT structures)
  - Higher doping = higher conductivity = lower efficiency
  - 180 nm = 10 Ω·cm, 45 nm = 0.1 Ω·cm

- 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

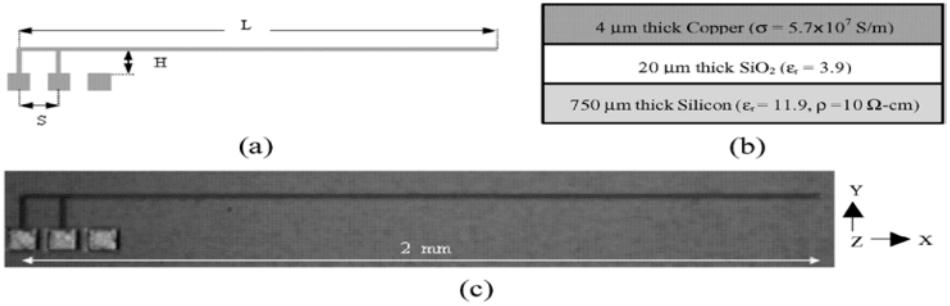
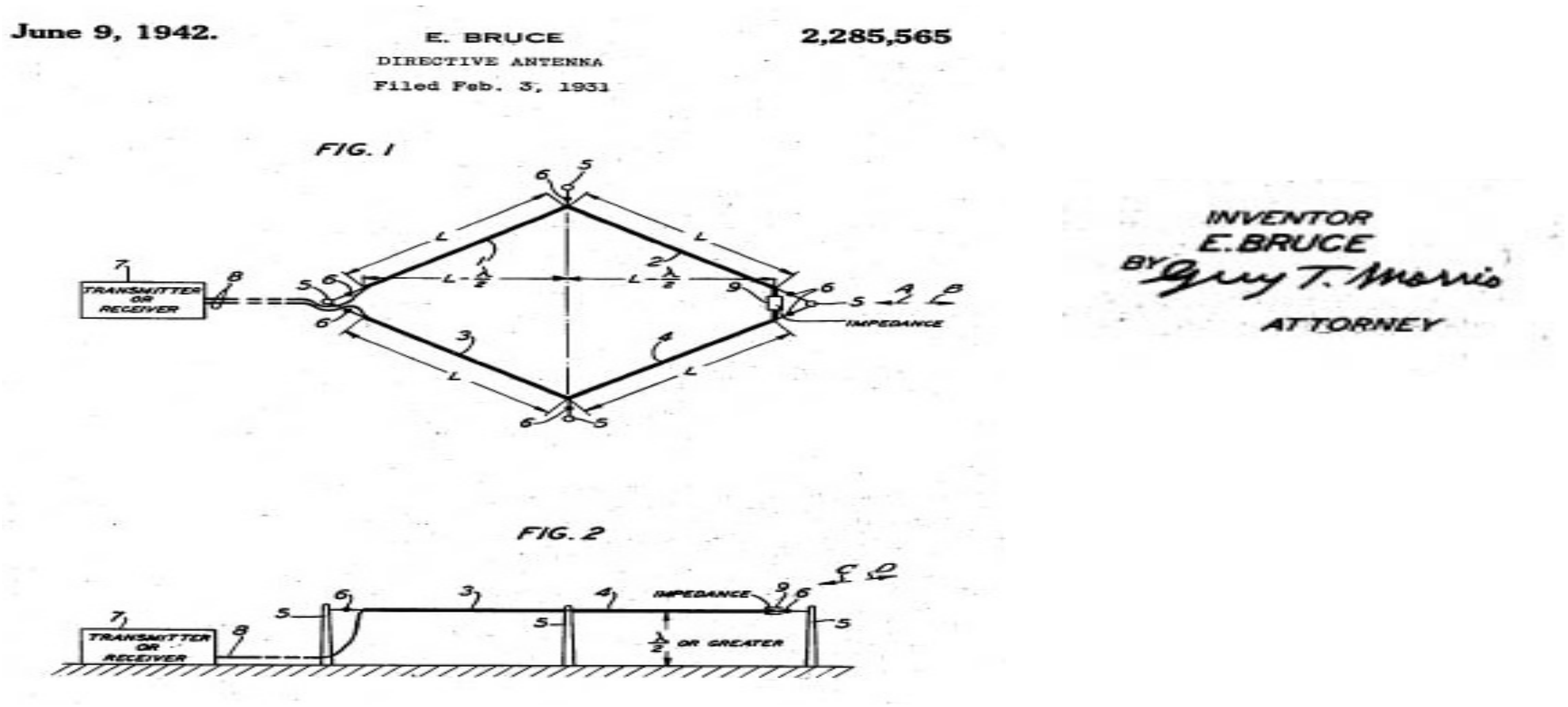


Fig. 1. On-chip inverted-F antenna: (a) layout, (b) cross-sectional view, and (c) top view photograph.

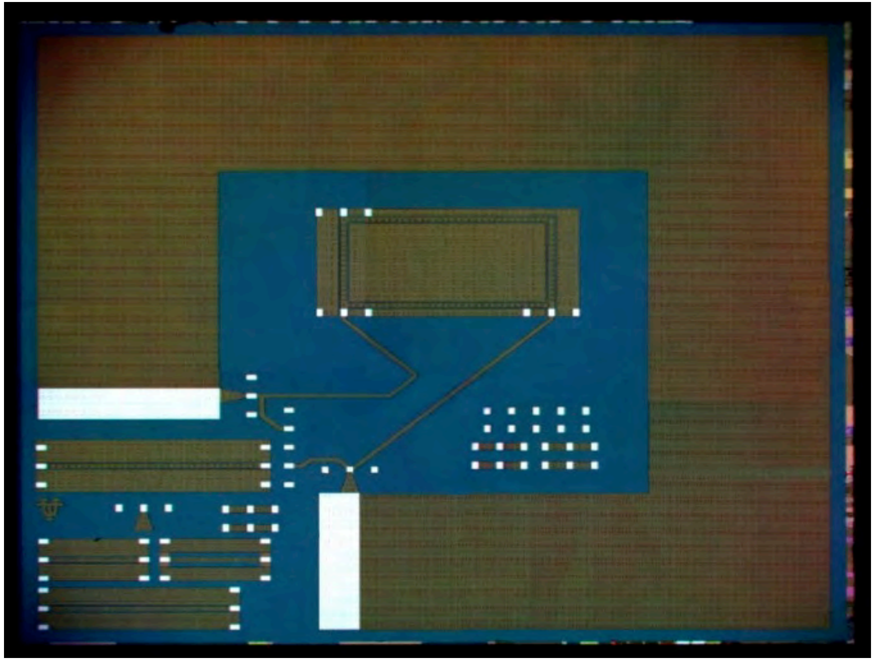
- Y.P. Zhang, M. Sun, L.H. Guo
- Planar Inverted F Antenna
- Nanyang Technological University, Singapore (2005)
- Gain: -19 dBi
- Efficiency: 1.7%
- CMOS with post-BEOL process @ 60 GHz
- 2 mm x 0.1 mm

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.

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.

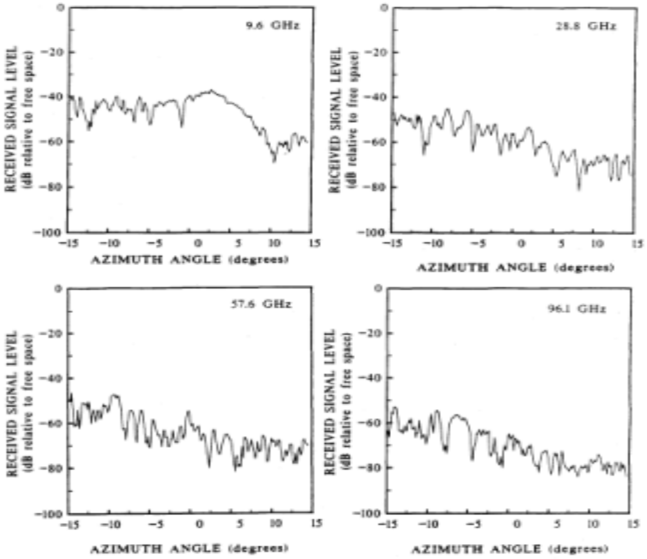
*above horizon

Cellular Spectrum above 3 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%

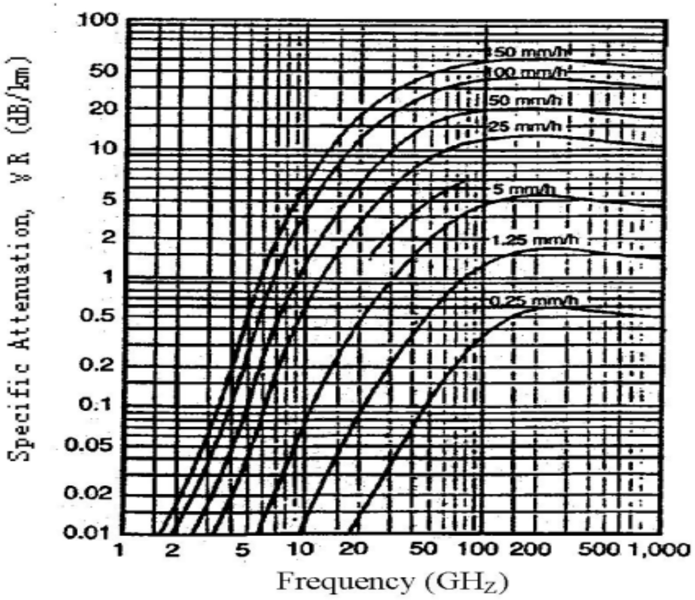
S.Y. Seidel and H.W. Arnold, "Propagation measurements at 28 GHz to investigate the performance of local multipoint distribution service (LMDS)," in IEEE Global Telecommunications Conference (Globecom), Nov. 1995, pp. 754-757.

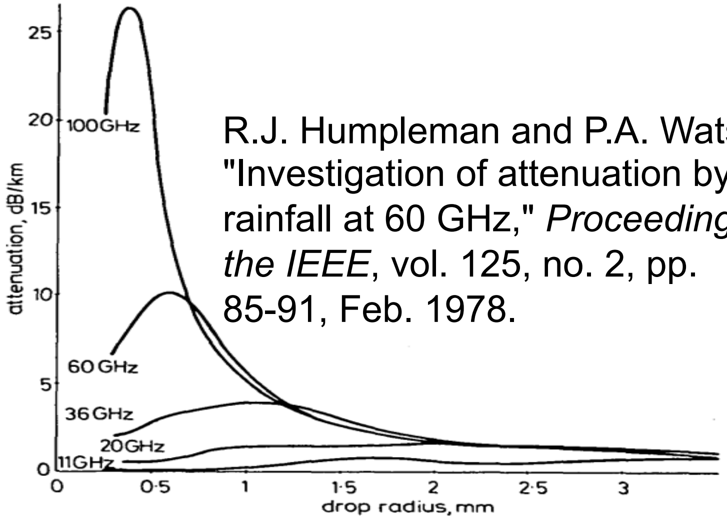
- Seidel measured signal strength up to 5 km for wireless backhaul at 28 GHz
- Coverage area increases with receiver antenna height
- Receiver antenna scanned only in azimuth direction
- Our study showed *elevation* angle scanning increases coverage significantly

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.

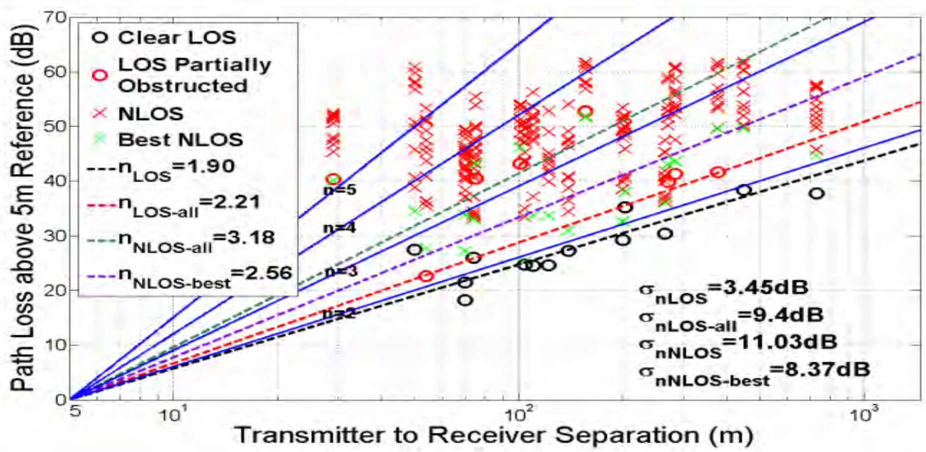




R.J. Humpleman and P.A. Watson, "Investigation of attenuation by rainfall at 60 GHz," *Proceedings of the IEEE*, vol. 125, no. 2, pp. 85-91, Feb. 1978.

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_0 is path loss measured at close-in distance d_0

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.

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

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

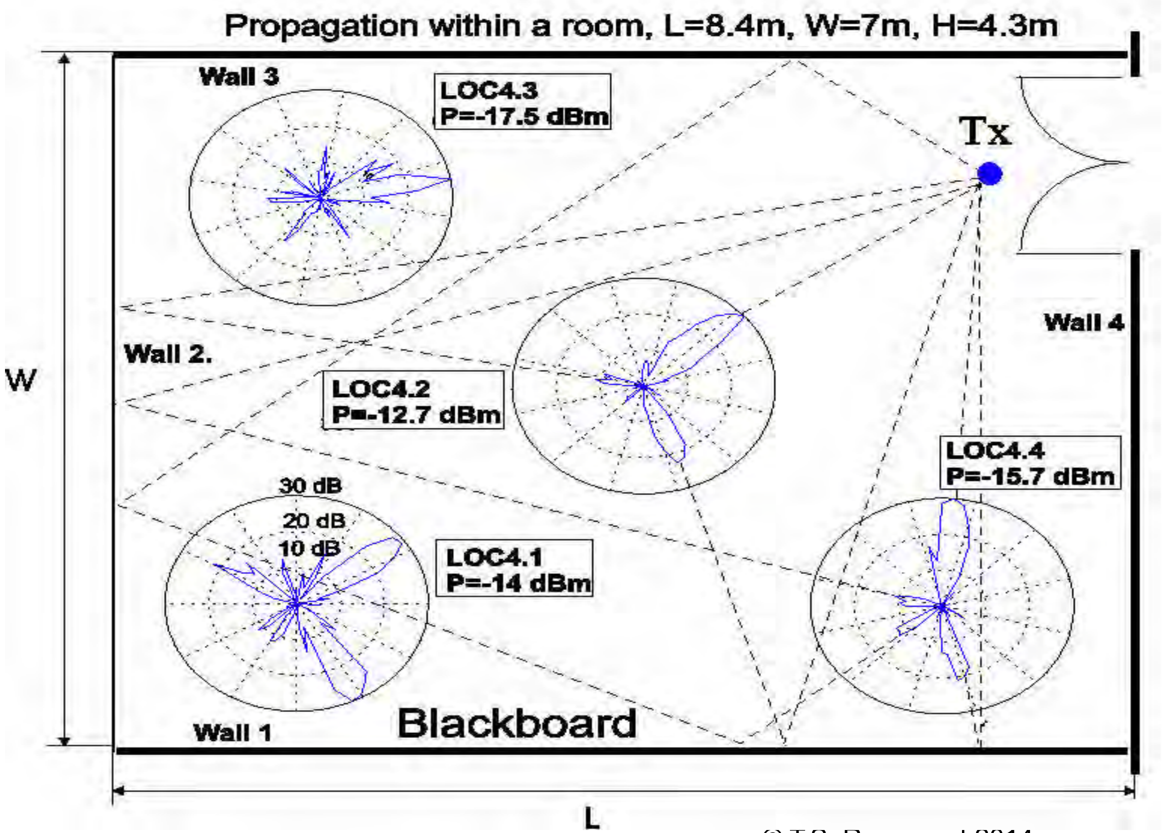
τ_i = Excess delay at time point i
P_i = Power at time point i

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

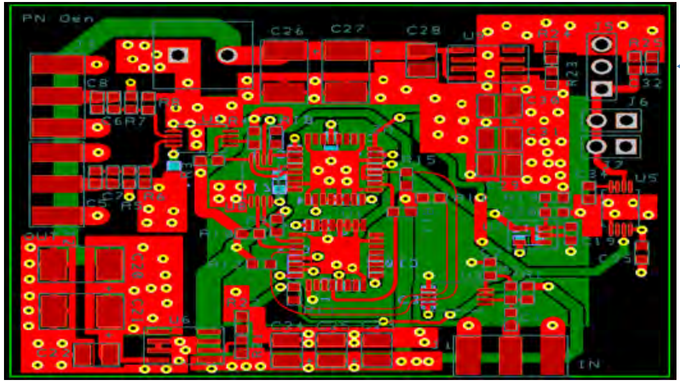


- AOA measurements are polar plots of received signal power versus receiver rotation angle.
- AOA data necessary for proper design of antenna array or switched beam antenna applications.

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.

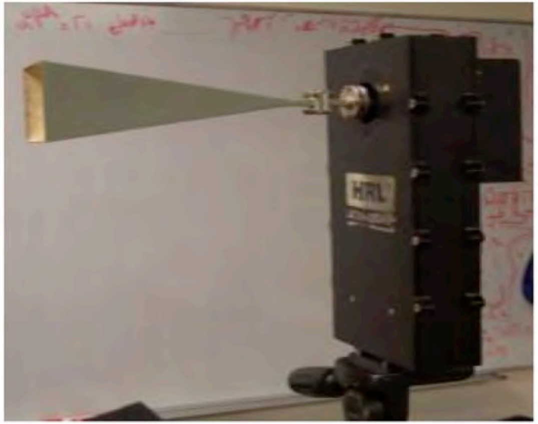
How to measure outdoor millimeter wave cellular channels?

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

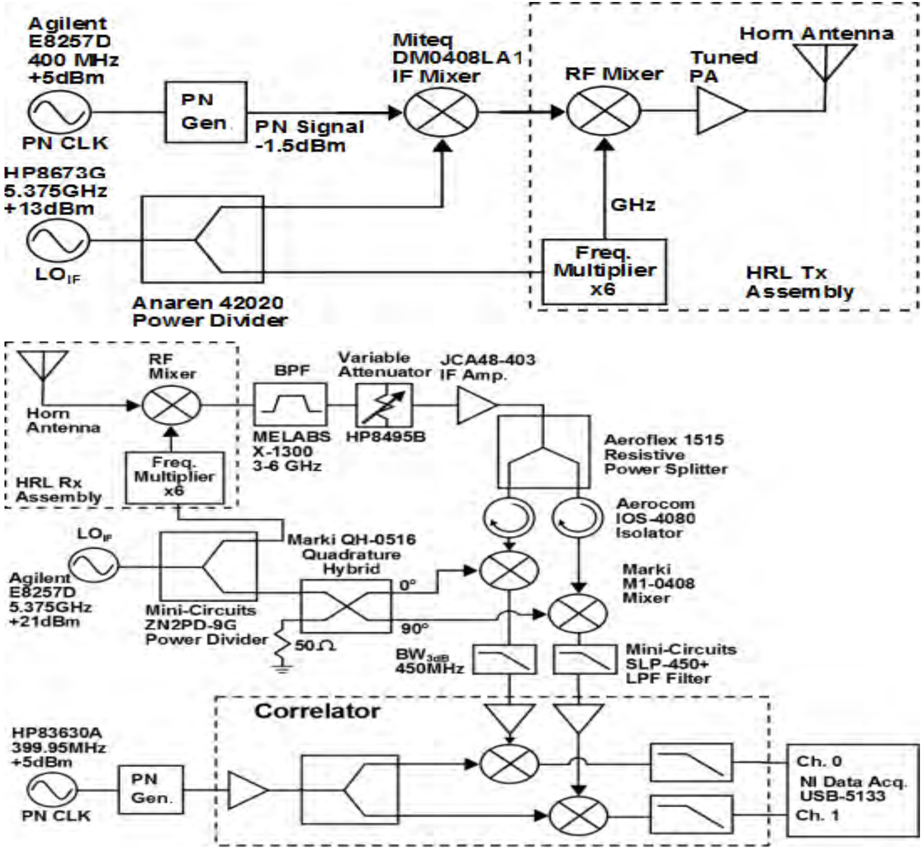
Transmitter

- 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



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

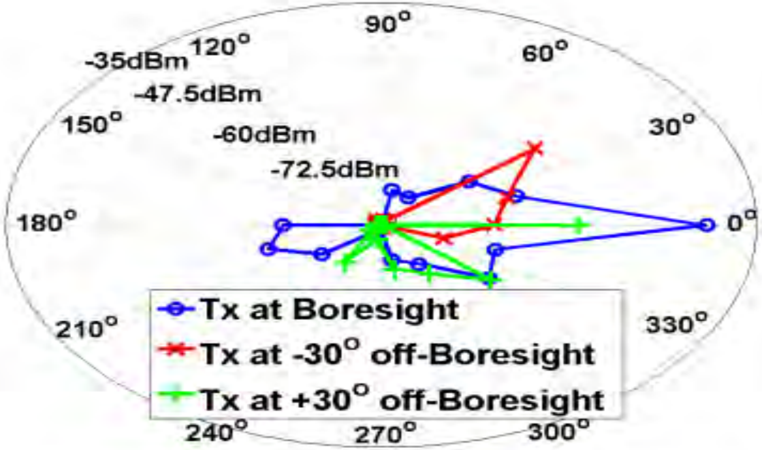
P2P (D2D) and cellular outdoor at 38 - 60 GHz

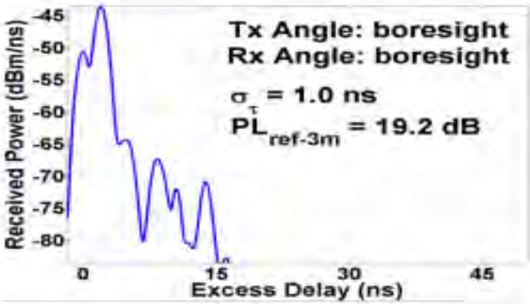
2011 Measurements at University of Texas

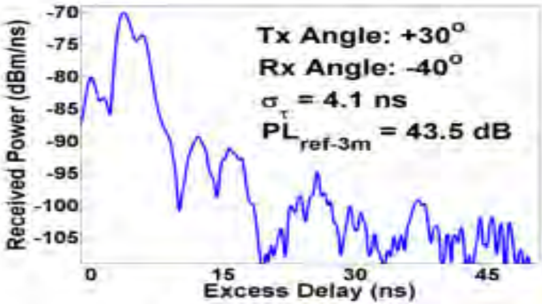
- Peer-to-Peer 38 and 60 GHz
  - Antennas 1.5m above ground
  - Ten RX locations (18-126m TR separation)
  - Both LOS and NLOS links measured using 8^o BW 25dBi gain antennas
- Cellular (rooftop-to-ground) at 38 GHz
  - Four TX locations at various heights (8-36m above ground) with TR separation of 29 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





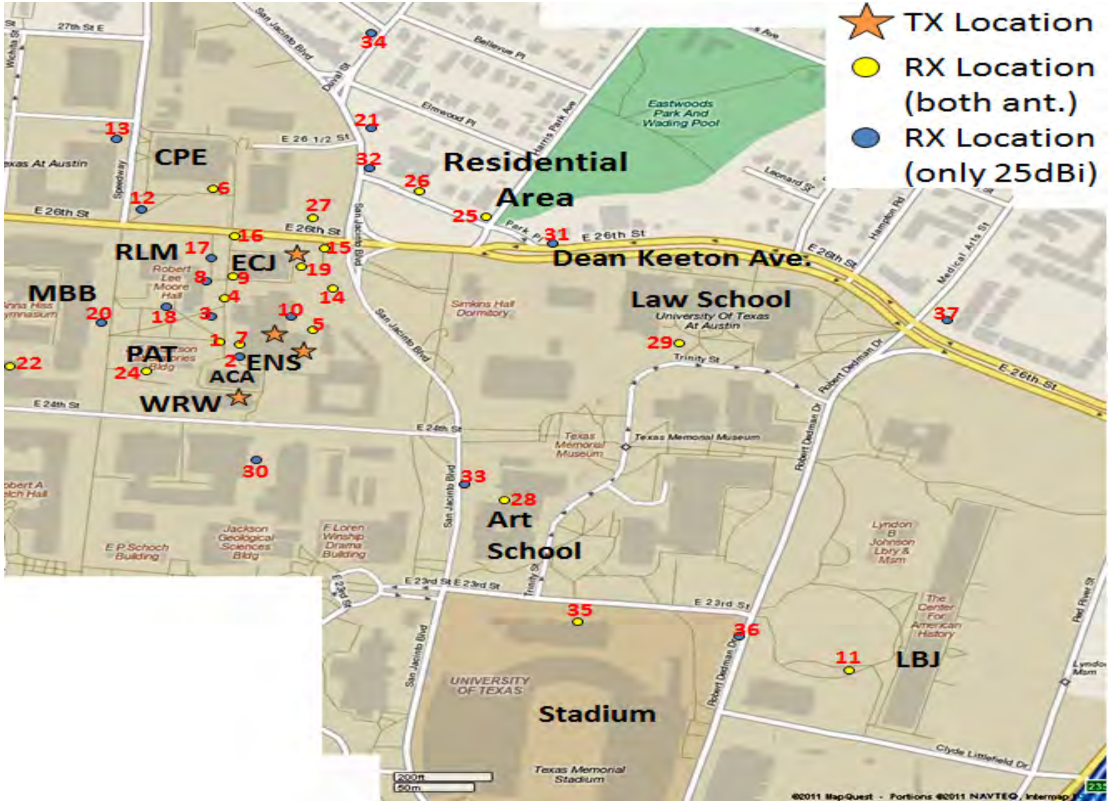


Cellular Measurement Map

Transmitter Locations

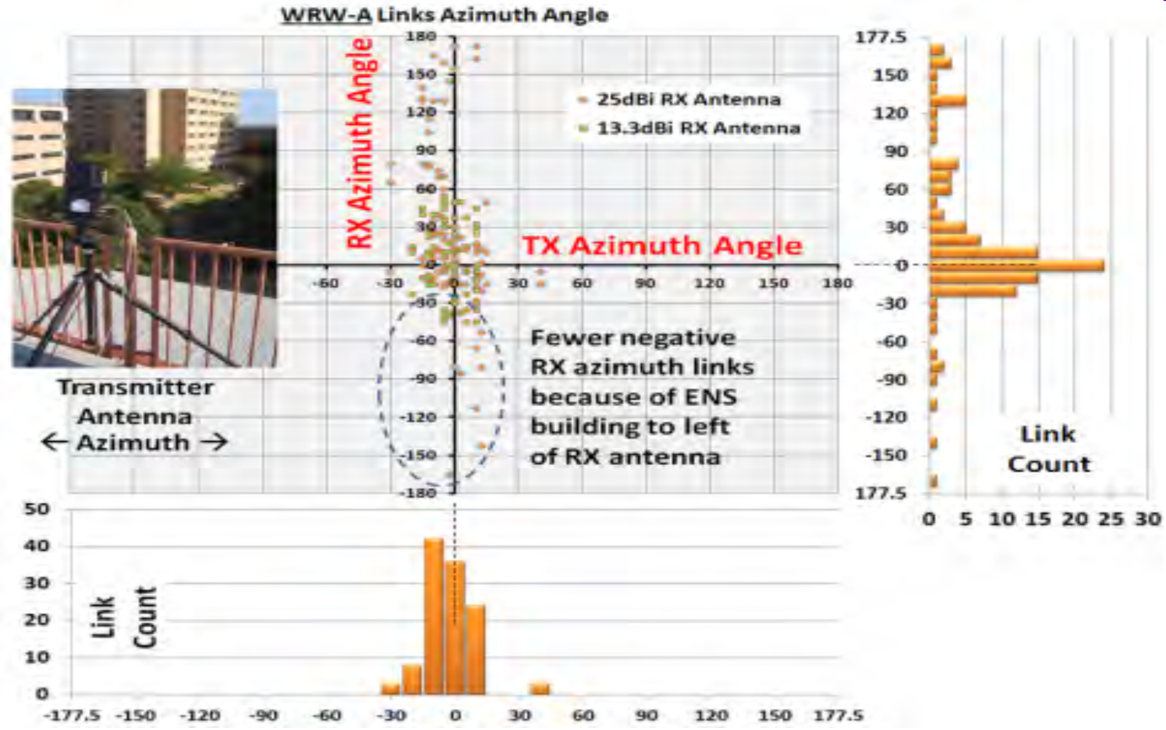
WRW-A ENS-A

ECJ ENS-B



38 GHz Cellular AOA

TX height 23m above ground

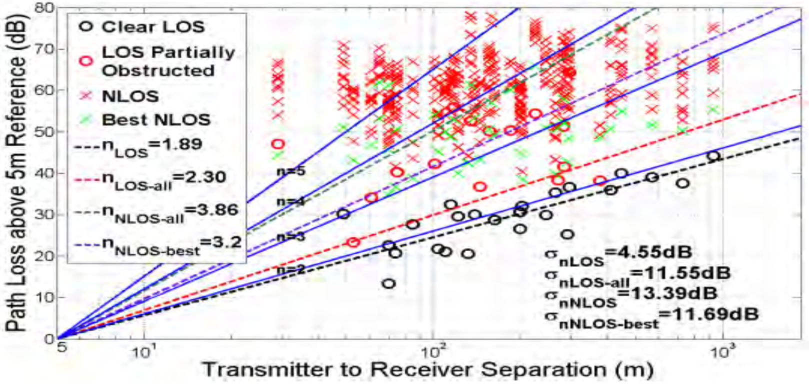


Histogram of RX angles for all links made using 25dBi antennas (10º bins)

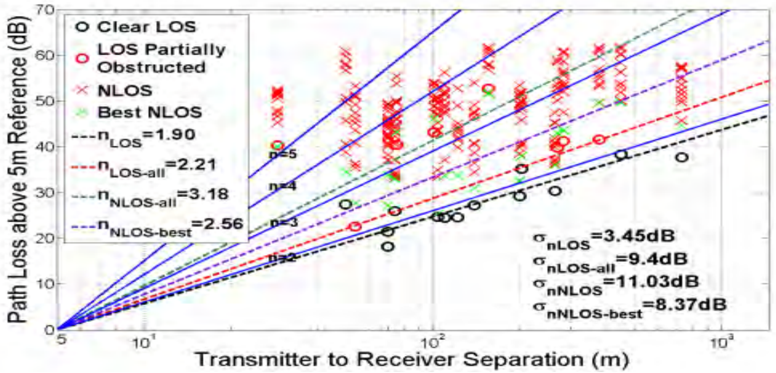
Histogram of TX angles for all links made using 25dBi antennas (10º bins)

38 GHz Cellular Path Loss

38 GHz Path Loss, 25dBi RX Antenna



38GHz Path Loss, 13.3dBi RX Antenna

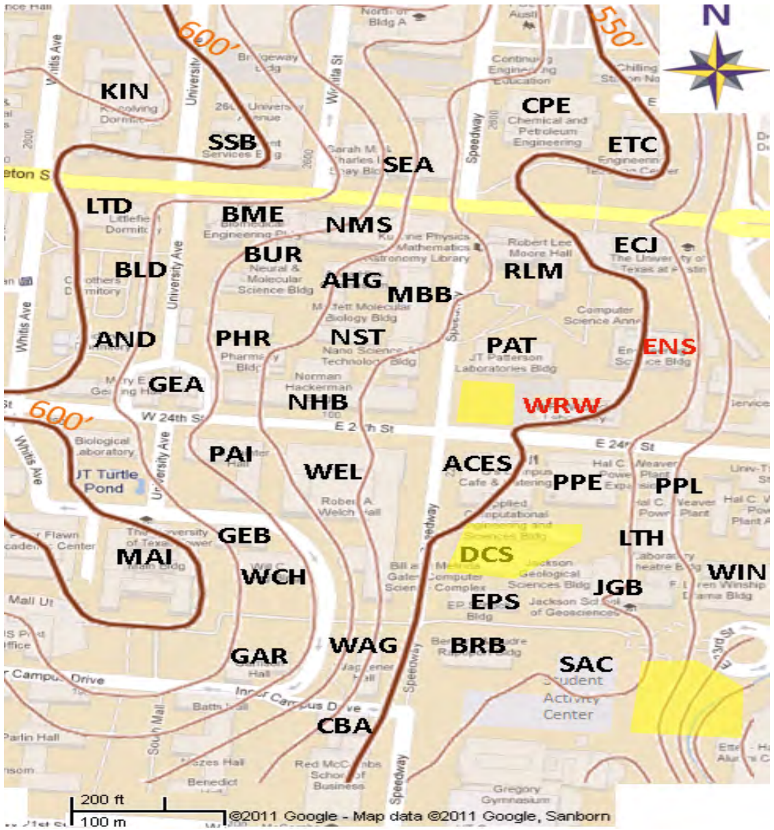


- Measurements performed using 13.3 and 25dBi horn antennas
- Similar propagation was seen for clear LOS links (n = 1.9)
- Wider beam antenna captured more scattered paths in the case of obstructed LOS
- Large variation in NLOS links

	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)

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

Measuring New York City The NYU Manhattan Campus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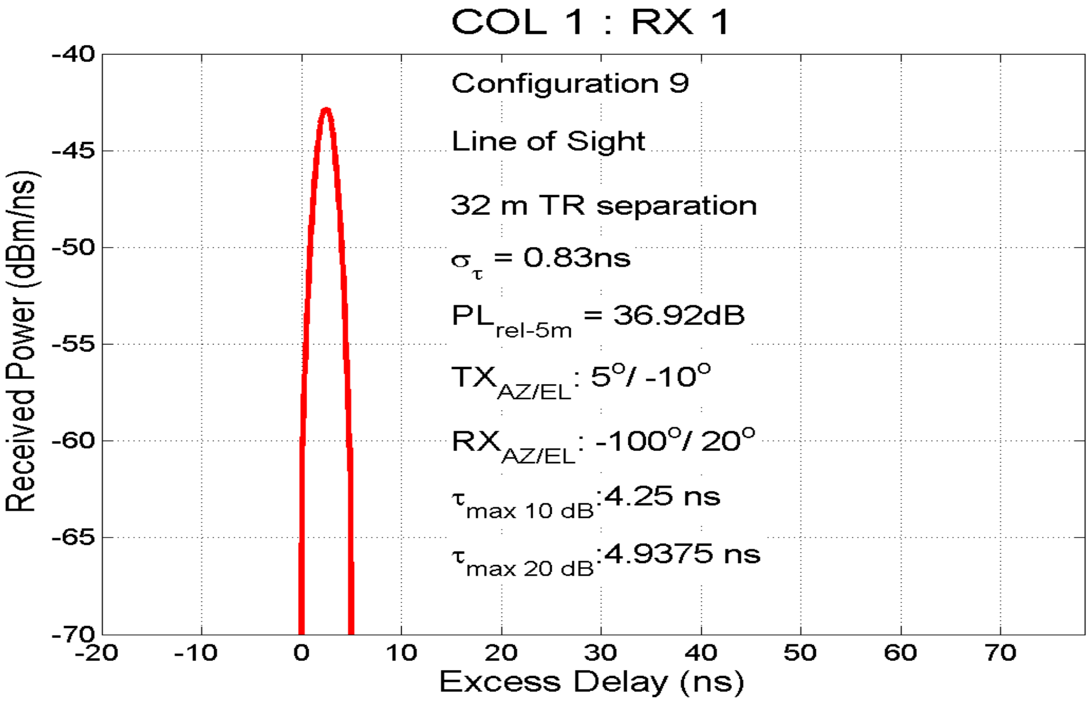
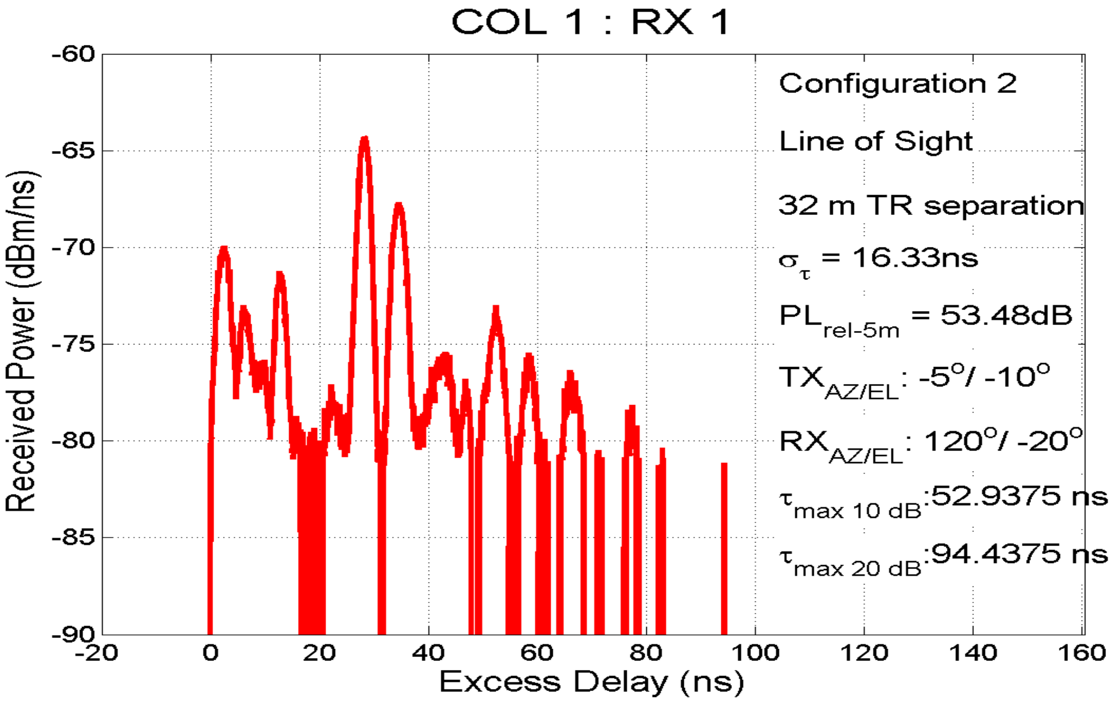
28 GHz LOS in Brooklyn



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

Manhattan measurement

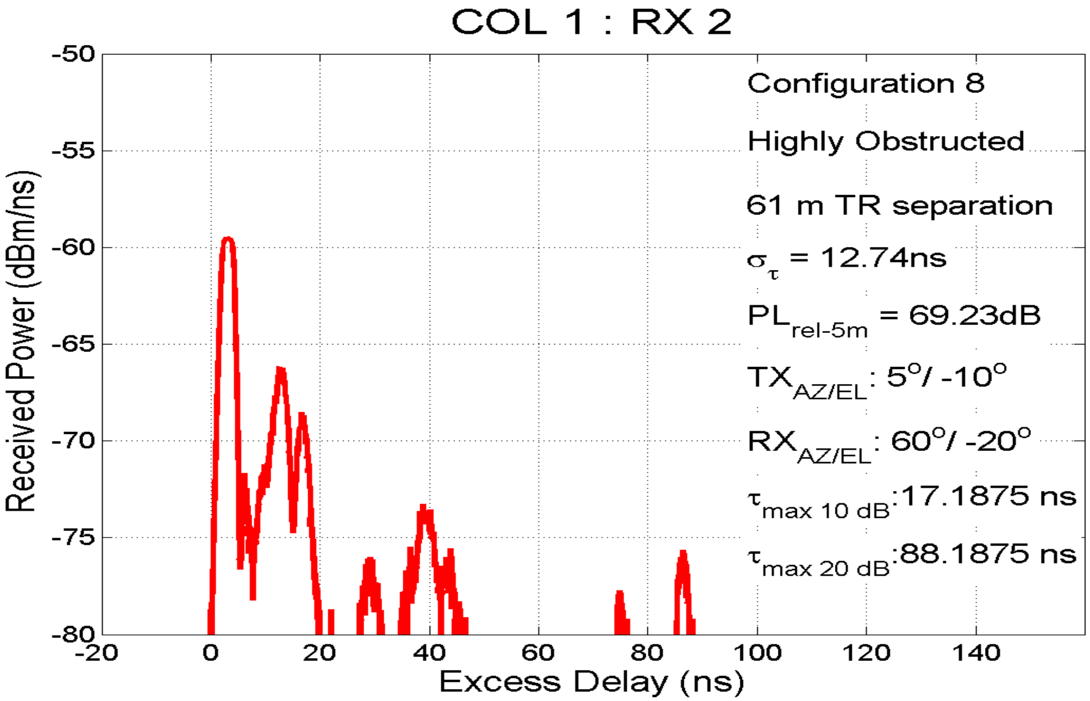
28 GHz LOS in Brooklyn



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

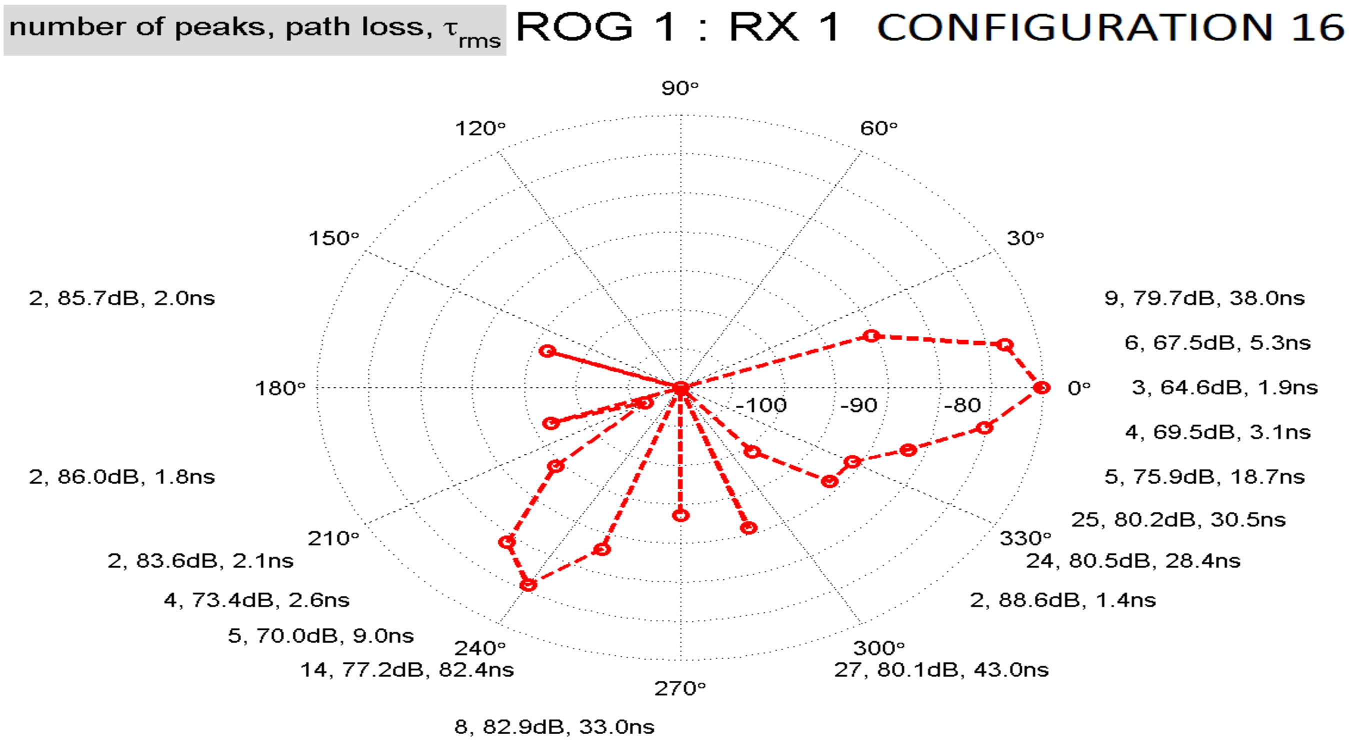
Manhattan measurement

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)

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, 200 m cells work at 28 and 73 GHz
- 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

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

- 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 Polytechnic School of Engineering
Brooklyn, NY 11201
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- **EXCITING NEW CENTER**: 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 Polytechnic (Electrical and Computer Engineering)
  - NYU Courant Institute (Computer Science)
  - NYU School of Medicine (Radiology) and world class hospital

- NYU WIRELESS faculty possess a diverse set of knowledge and expertise:
  - Communications (DSP, Networks, RF/Microwave, Antennas, Circuits)
  - Medical applications (Anesthesiology, EP Cardiology, MRI, Compressed sensing)
  - Computing (Graphics, Data mining, Algorithms, Scientific computing)
  - Current in-force funding:
  - Over $10 Million/annually from NSF, NIH, and Corporate sponsors

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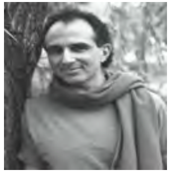

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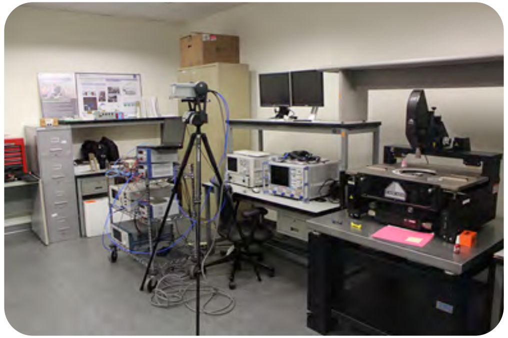

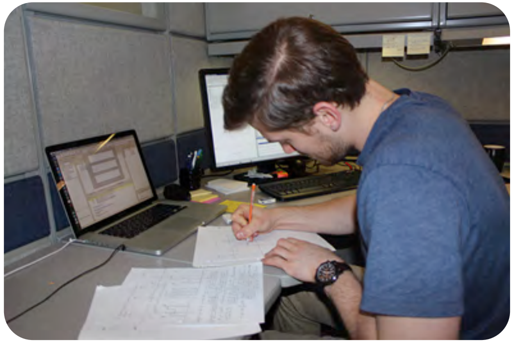

About NYU

New York University

- One of 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 #32 in 2013 USNWR National University Ranking
    - (GA Tech is 36, UT Austin is 46)

NYU WIRELESS Mission and Expertise

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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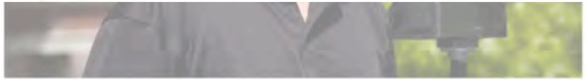
"Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," a recent journal paper co-authored by NYU WIRELESS Director Theodore (Ted) Rappaport and his students, was among the top 50 papers downloaded from the entire library of IEEE in the month of June. Ranked as the 36th most popular paper 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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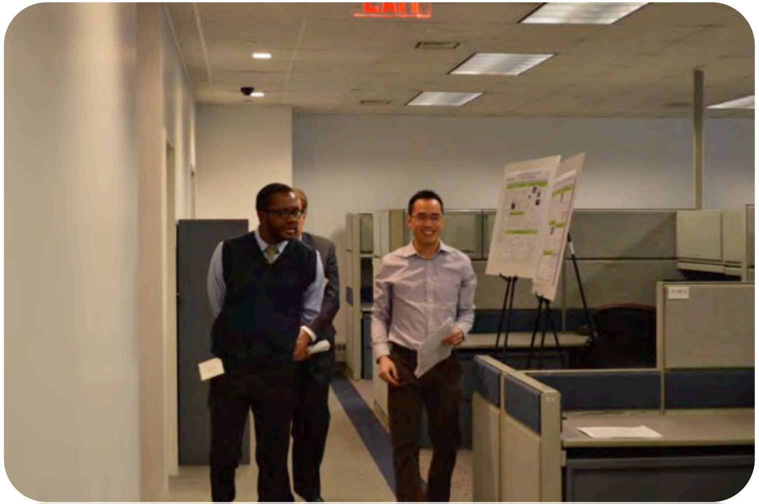
Board Meeting and Recruitment Day

Board Meeting and Recruitment Day



NYU WIRELESS students showcase their research to the board

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

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Robert (Bob) J. Duffy

Lieutenant Governor, New York State

Luncheon Speaker

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Great lineup of speakers from academia and industry

The Exhibits

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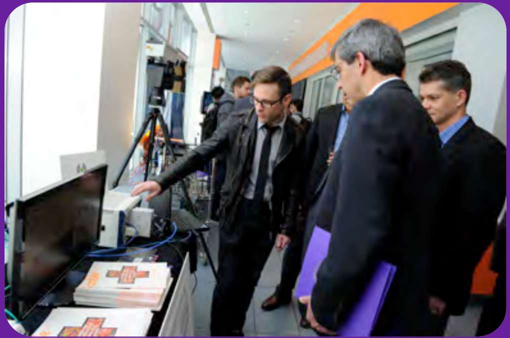

Special Exhibits by Agilent Technologies, Intel, InterDigital, National Instruments, NSN, NYU WIRELESS, Prentice Hall Professional and Rohde & Schwarz

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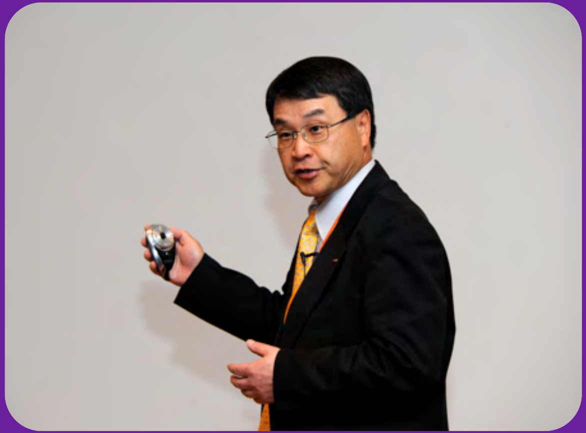
Special announcement and unveiling



DOCOMO's 5G vision
Dr. Seizo Onoe, DOCOMO

Platform Approach to Design of Next Generation Wireless Systems

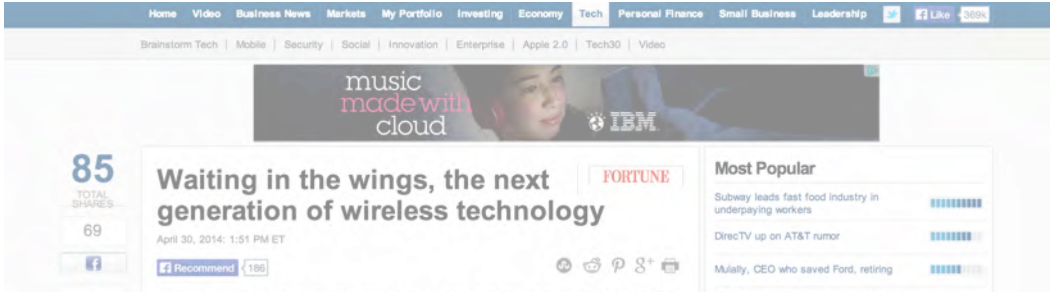
Eric Starkloff, Sr. VP, National Instruments

Panel Discussion: Creating a Partnership for 5G Channel Models

Samsung's Vision

In the Press

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.

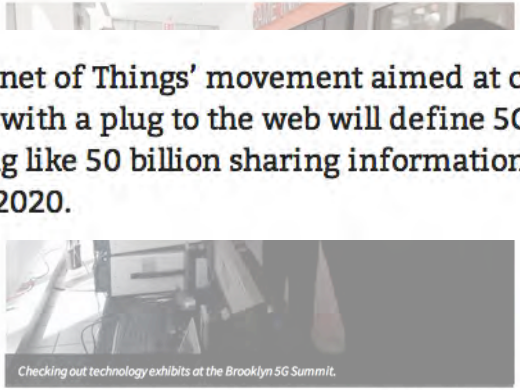
In the Press

Microwave Journal

Professor Rappaport and NSN ran a great inaugural event that attracted the best minds in the industry and academic world doing advanced research on potential 5G technologies. It is surely going to be a high level annual event for many years to come as these technologies are tested and verified eventually leading to a standard.

In the Press

Technical.ly



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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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'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.

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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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

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Recent Publications related to this

NYU WIRELESS

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.

J. N. Murdock, E. Ben-Dor, Y. Qiao, J. I. Tamir, T. S. Rappaport, “A 38 GHz Cellular Outage Study for an Urban Outdoor Campus Environment,“ IEEE Wireless Communications and Networking Conference (WCNC 2012), April 2012.

J. I. Tamir, T. S. Rappaport, Y. C. Eldar, A. Aziz, "Analog Compressed Sensing for RF Propagation Channel Sounding,“ IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2012), March 2012.

T. S. Rappaport, Y. Qiao, J. I. Tamir, J. N. Murdock, E. Ben-Dor, "Cellular Broadband Millimeter Wave Propagation and Angle of Arrival for Adaptive Beam Steering Systems (Invited Paper),“ IEEE Radio and Wireless Symposium (RWS), January 2012.

E. Ben-Dor, T. S. Rappaport, Y. Qiao, S. J. Lauffenburger, "Millimeter-Wave 60 GHz Outdoor and Vehicle AOA Propagation Measurements Using a Broadband Channel Sounder,“ IEEE Global Communications Conf. (Globecom 2011), Houston, December 2011.

J. N. Murdock, T. S. Rappaport, "Consumption Factor: A Figure of Merit for Power Consumption and Energy Efficiency in Broadband Wireless Communications,” IEEE Globecom, Broadband Wireless Access Workshop, Houston, December 2011.

J.N. Murdock, T. S. Rappaport, “Power Efficiency and Consumption Factor Analysis in Broadband Millimeter Wave Cellular Networks,” IEEE Global Communications Conf.. (Globecom) , December 2012, Anaheim, CA