NEW YORK UNIVERSITY

NYU WIRELESS
World's First Research Center with ECE, CS, and MEDICINE

For more information, contact Prof. Ted Rappaport at tsr@nyu.edu

NYU·poly
POLYTECHNIC INSTITUTE OF NYU

WICAT
WIRELESS INTERNET
Center for Advanced Technology

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 (Anesthesiology ,EP Cardiology, MRI, Compressed sensing)
  - Computing (Graphics, Data mining, Algorithms, Scientific computing)

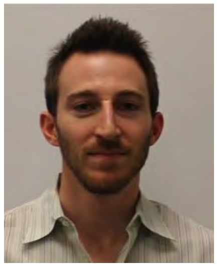
  Current in-force funding:
  - ~ $10 Million/annually from NSF, NIH, and Corporate sponsors

NEW YORK UNIVERSITY

NYU WIRELESS

NYU WIRELESS Faculty

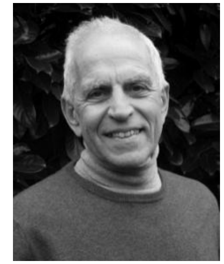

Henry Bertoni
Radio Channels
POLY


Ryan Brown
RF Coils/Imaging
NYUMC


Justin Cappos
Systems Security
POLY


Christopher Collins
MRI Imaging
NYUMC


Elza Erkip
Communications
POLY

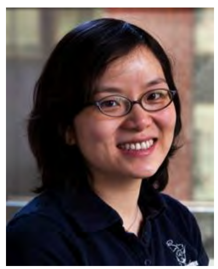

David Goodman
Communications
POLY


Mike Knox
RF/Microwaves
POLY

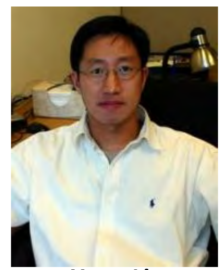

Marc Bloom
Anesthesiology
NYUMC


Ricardo Lattanzi
MRI Optimization
NYUMC

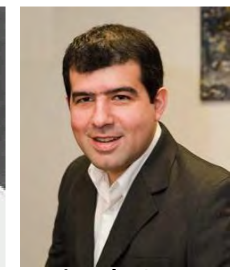

Daniel O'Neill
Anesthesiology
NYUMC


Jinyang Li
Networks
COURANT


Pei Liu
Wireless Networks
POLY


Yong Liu
Networks
POLY


I-Tai Lu
Electromagnetics
POLY

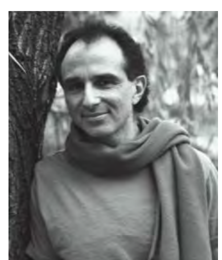

Ricardo Otazo
MRI Imaging
NYUMC


Shivendra Panwar
Cross-layer Design
POLY


Sundeep Rangan
Communications
POLY

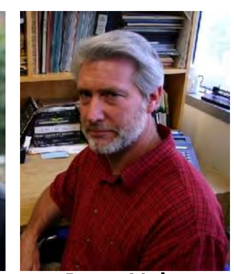

Ted Rappaport
Communications
POLY


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
POLY

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WICAT

NYU WIRELESS Industrial Affiliates

NATIONAL INSTRUMENTS™

SAMSUNG

INTERDIGITAL®

L3

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 #33 in 2012 USNWR National University Ranking

(GA Tech is 36, UT Austin is 45)

About NYU School of Medicine

NYU School of Medicine / NYU Langone Medical Center

- Top 10 in the US and #1 in New York for clinical research
- World-class patient-centered integrated academic medical center in Healthcare, biomedical research (http://www.med.nyu.edu/about-us)
- Approximately $250,000,000 /yr. in research grants (mainly NIH)
- Department of Radiology is global leader in RF engineering and technology development for biomedical imaging, MRI
- Department of Surgery desires wireless solutions

About NYU Courant

NYU Courant Institute of Mathematical Sciences

- The Courant Institute of Mathematical Sciences is ranked #1 in applied mathematical research, #5 in citation impact worldwide, and #12 in citation worldwide.
- Computer Science program has top-ranked computer graphics rendering, game development, video recognition programs.

SAMPLE RESEARCH PROJECTS AT NYU WIRELESS

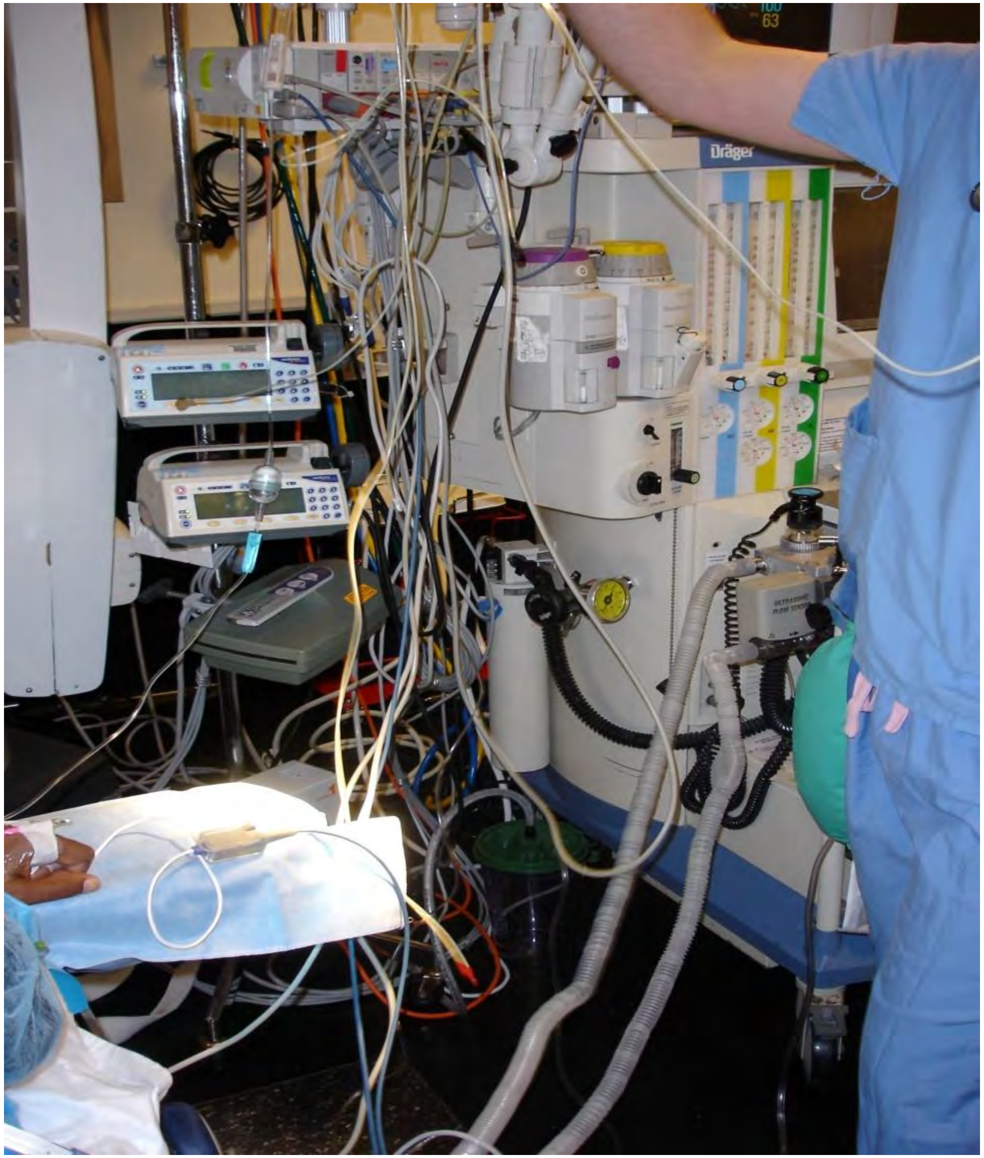
Interdisciplinary across NYU

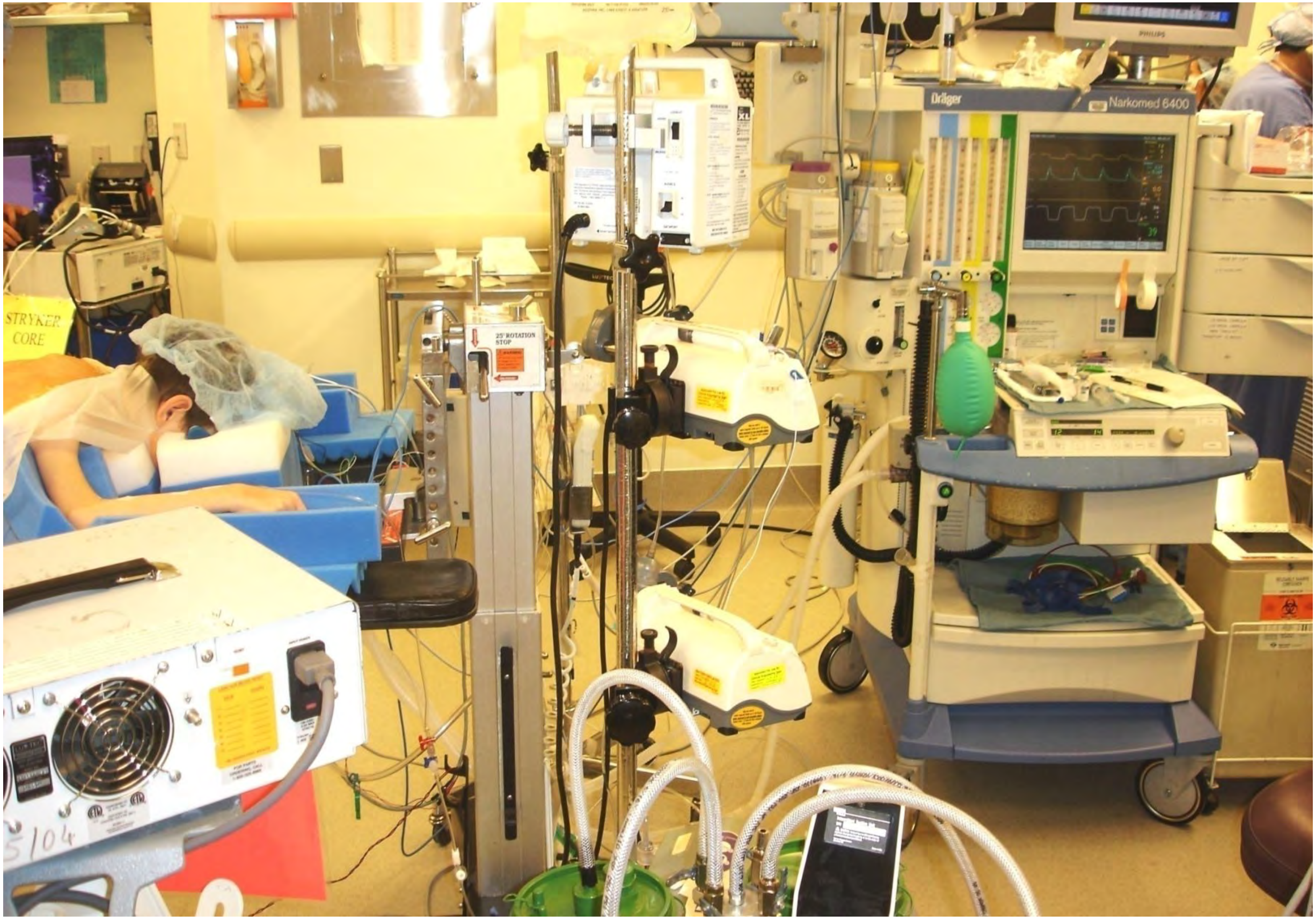
Creating a new kind of student

Vast opportunities for Industry

NYU is uniquely positioned to change the world – and we are!

Why Wireless and Medicine?

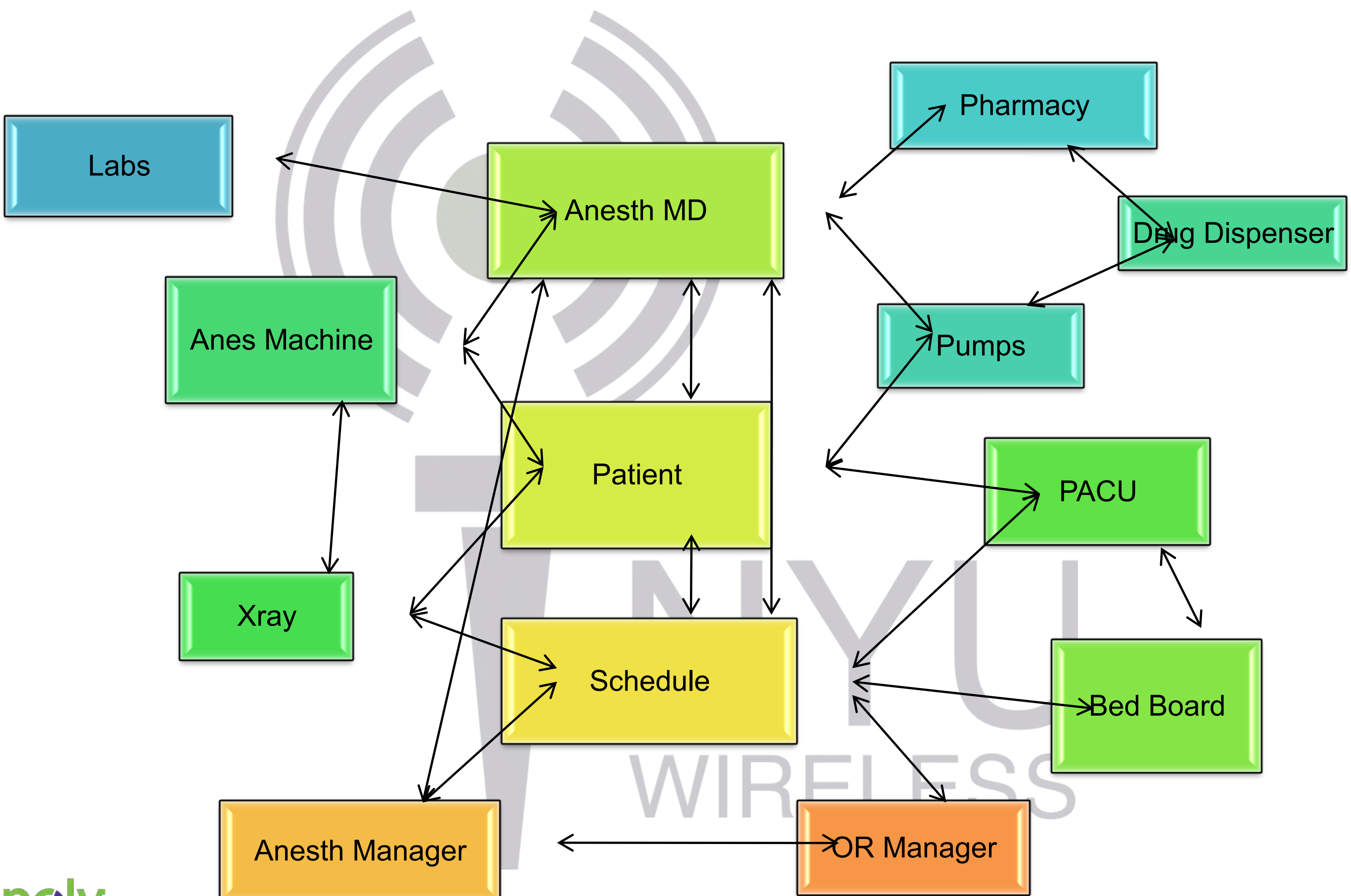



STRYKER
CORE
25° ROTATION
STOP
Dräger
Narkomed 6400
PHILIPS

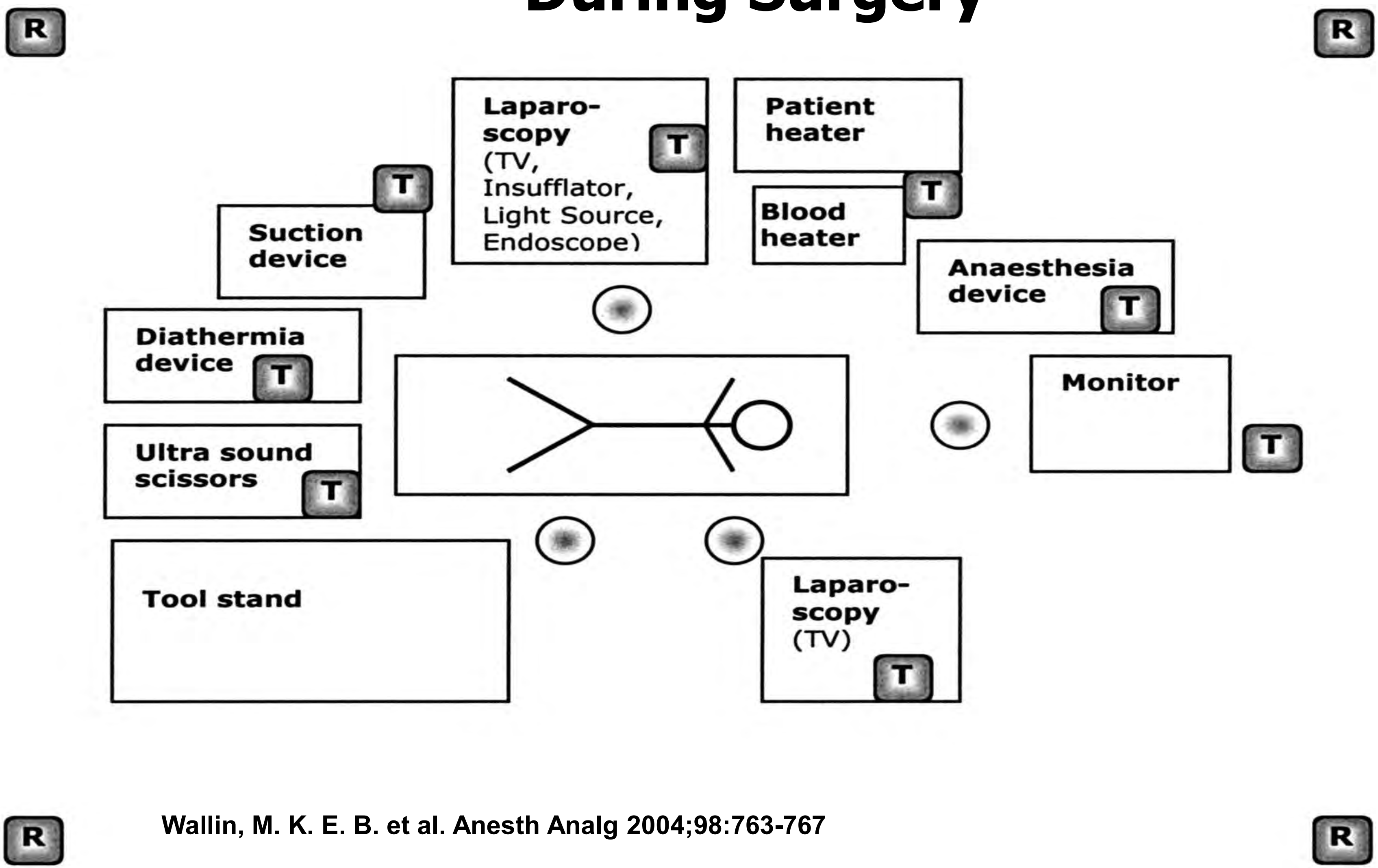
The Problems

- 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

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

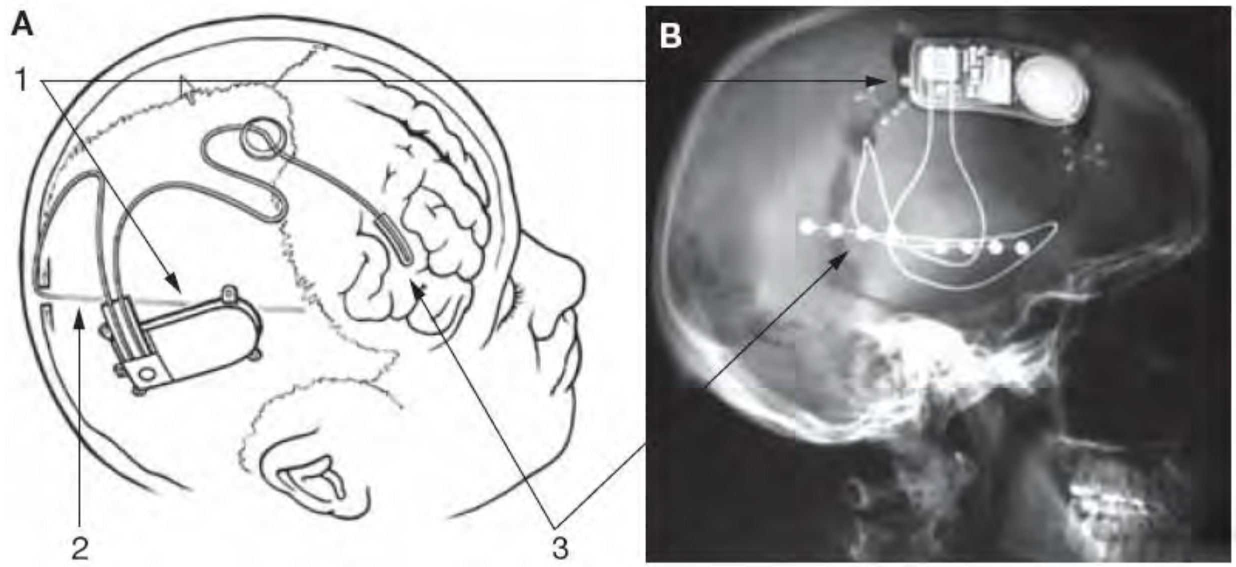
- EP is very technology-intensive
- A broad range of signal processing and imaging equipment is required for even the most basic EP procedure
- The "wireless revolution" has not yet hit the EP lab
- The EP physician has historically functioned as the hardware interface between the various equipment required
- 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

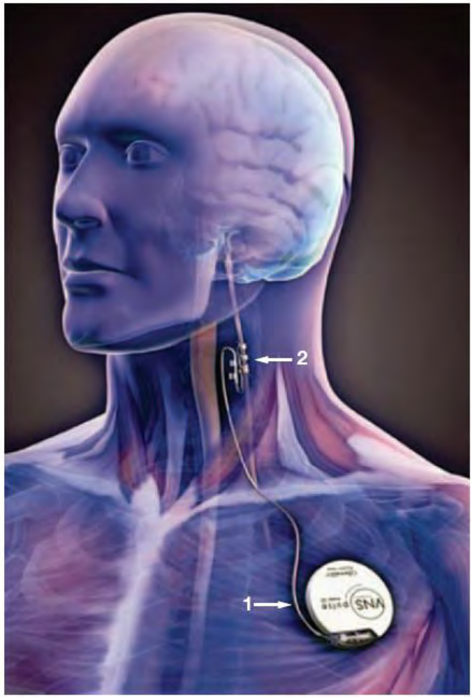
- Despite recent advances in technology and success in catheter ablation techniques, many vexing problems remain. Doctors need:
- Wireless connectivity within the EP lab
- Universal user interface among various technologies
- Improved temporal and spatial resolution of mapping techniques
- Improved accuracy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

Implantable Devices for Medicine

- Implantable devices have evolved
- Electrodes have not improved

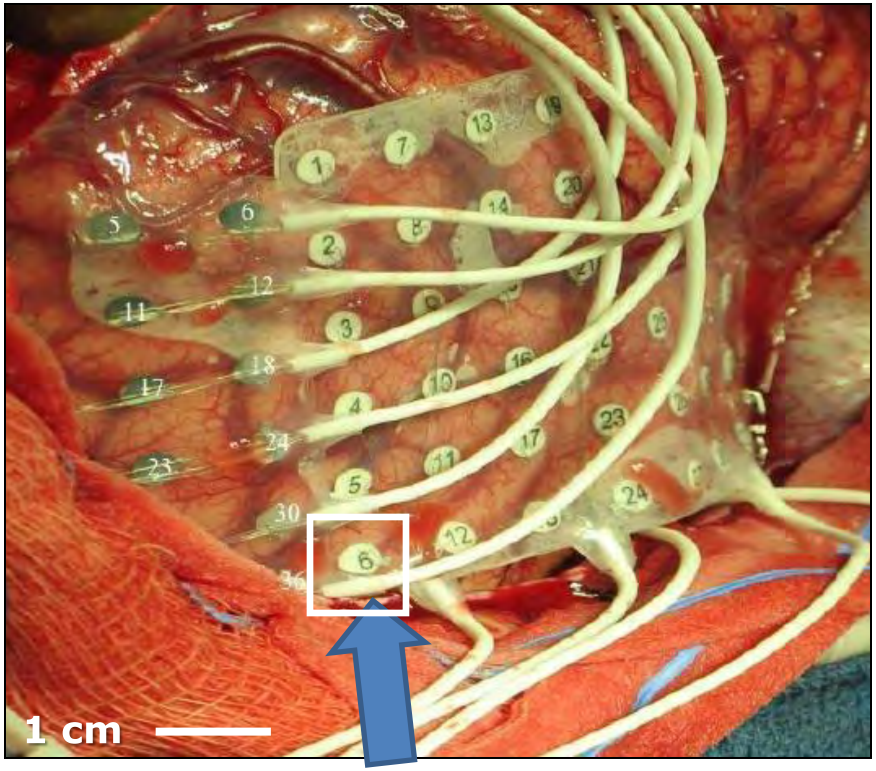


NeuroPace Responsive Neurostimulator (RNS®)



Vagus Nerve Stimulator
Cyberonics, Inc.

"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

Flexible Silicon Electronics to Improve Electrode Arrays in the Body

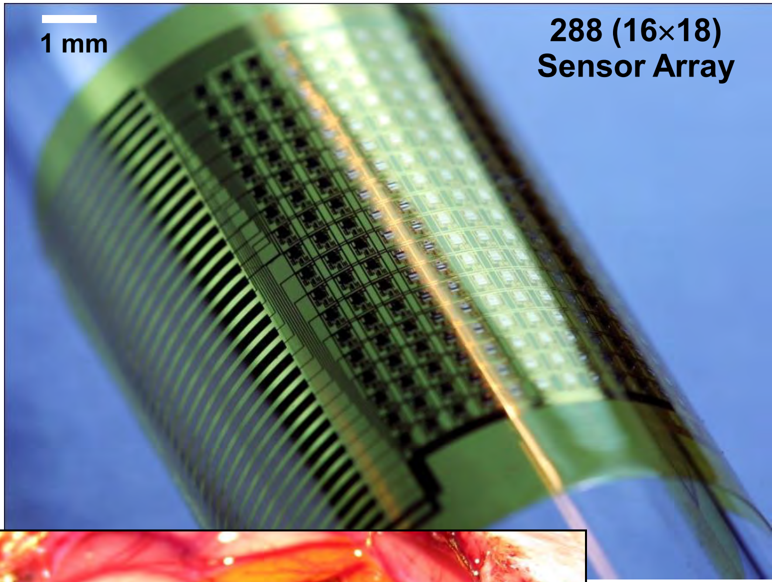
Conformal to Brain
- 25 µm thickness
- 2.8 µm using biodegradable silk

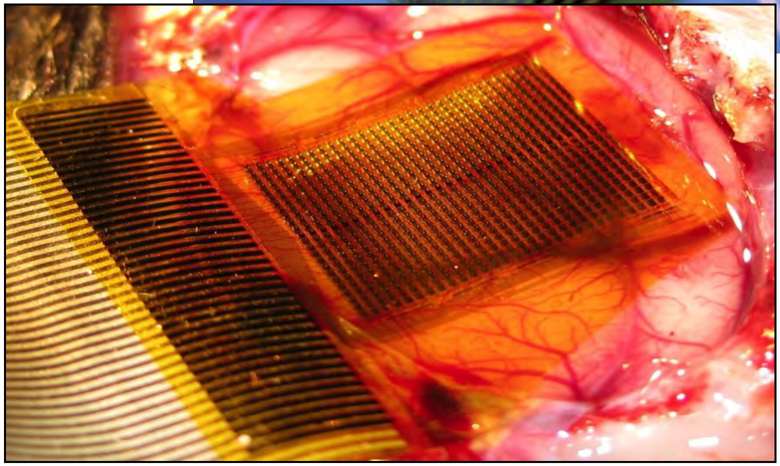
High spatial resolution
- **1024 <u>Active</u>** Electrodes
- 250 µm spacing

High temporal resolution
- Up to 12.5 kHz sampling

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

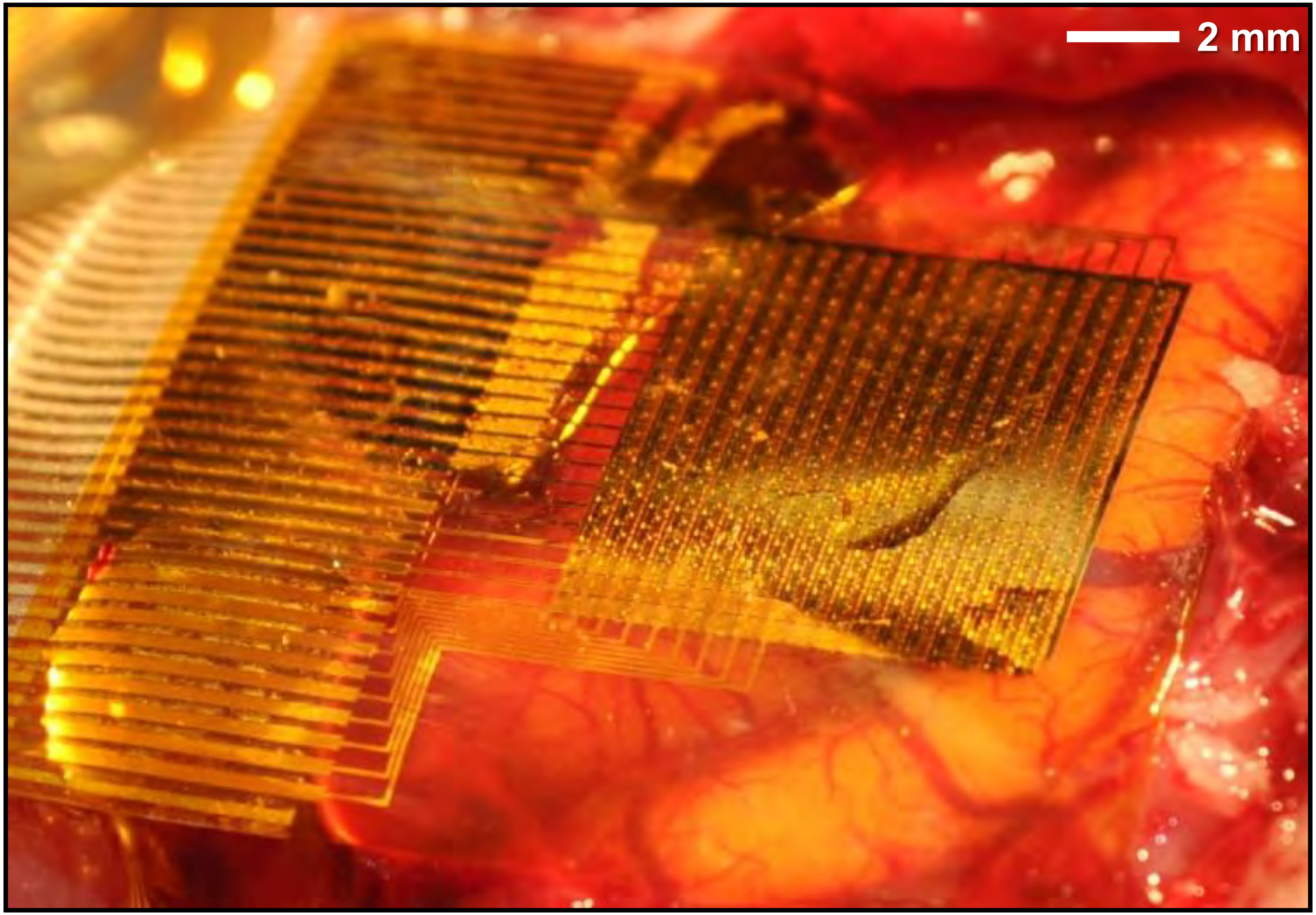
Scalable
- 1000s of electrodes
- Fewer wires





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

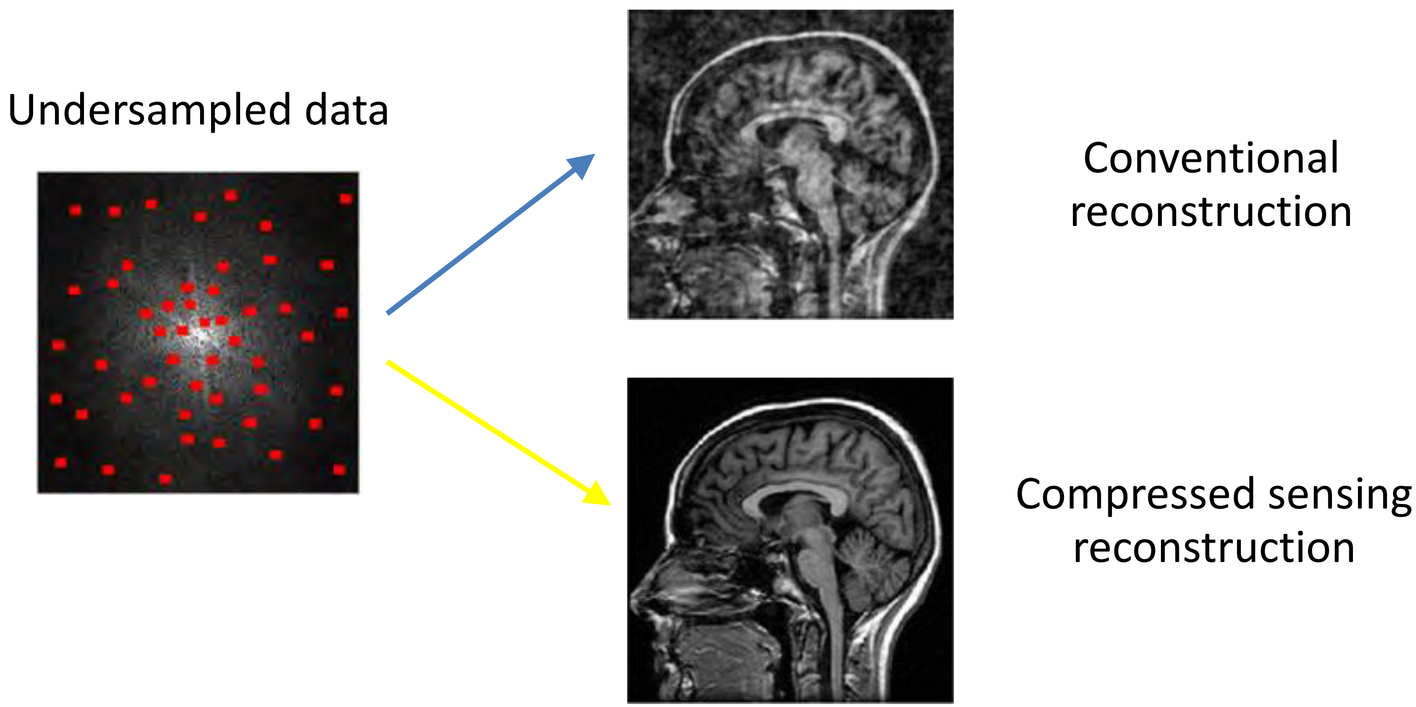
Electrode on Brain



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

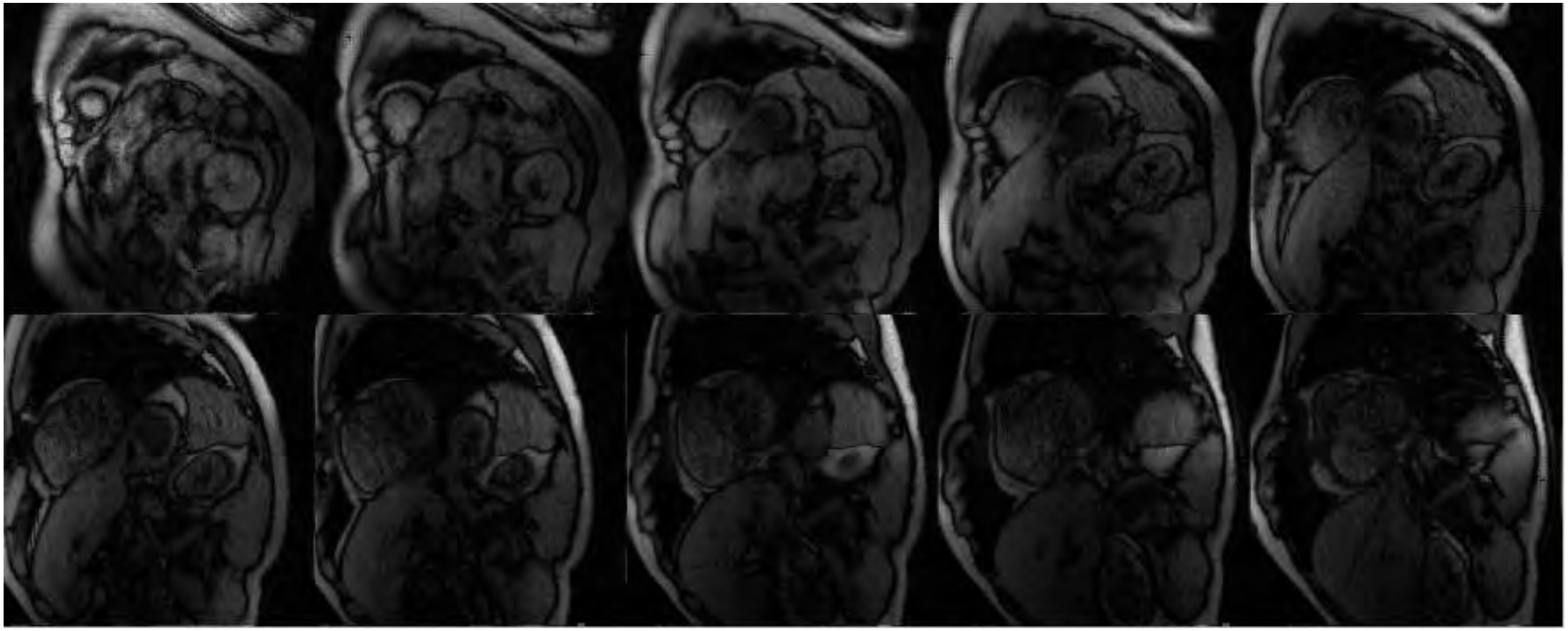
Compressed Sensing for Medicine

- Exploit compressibility/sparsity of medical images to speed up MRI by pre-compressing data acquisition



First-Pass Cardiac Perfusion MRI

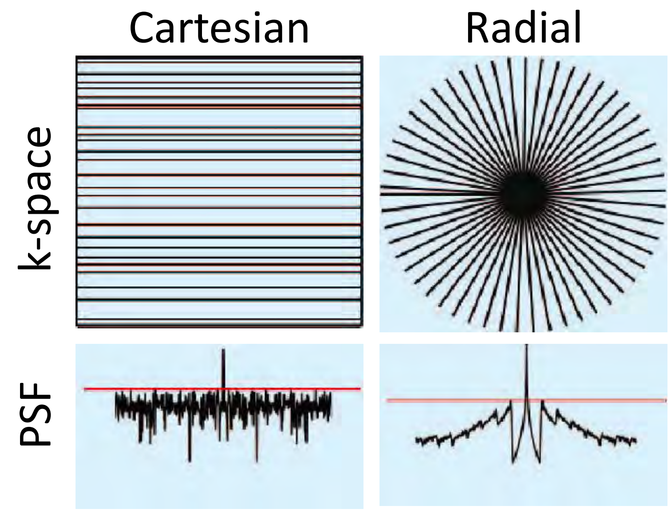
- 8-fold acceleration
- 10 slices per heartbeat
- Temporal resolution = 60ms/slice
- Spatial resolution (in-plane) = 1.7 mm



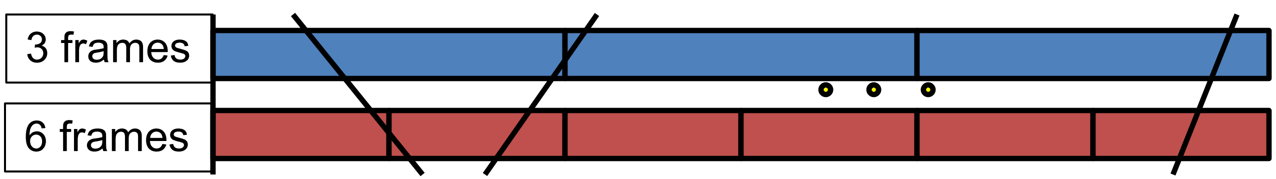
Otazo et al. Magn Reson Med. 2010; 64:767-76

Non-Cartesian Compressed Sensing MRI

- Non-Cartesian acquisition trajectories (radial, spiral) offer inherent incoherence
  - – No need for random undersampling



- Continuous data acquisition and reconstruction with arbitrary temporal resolution (golden-angle)

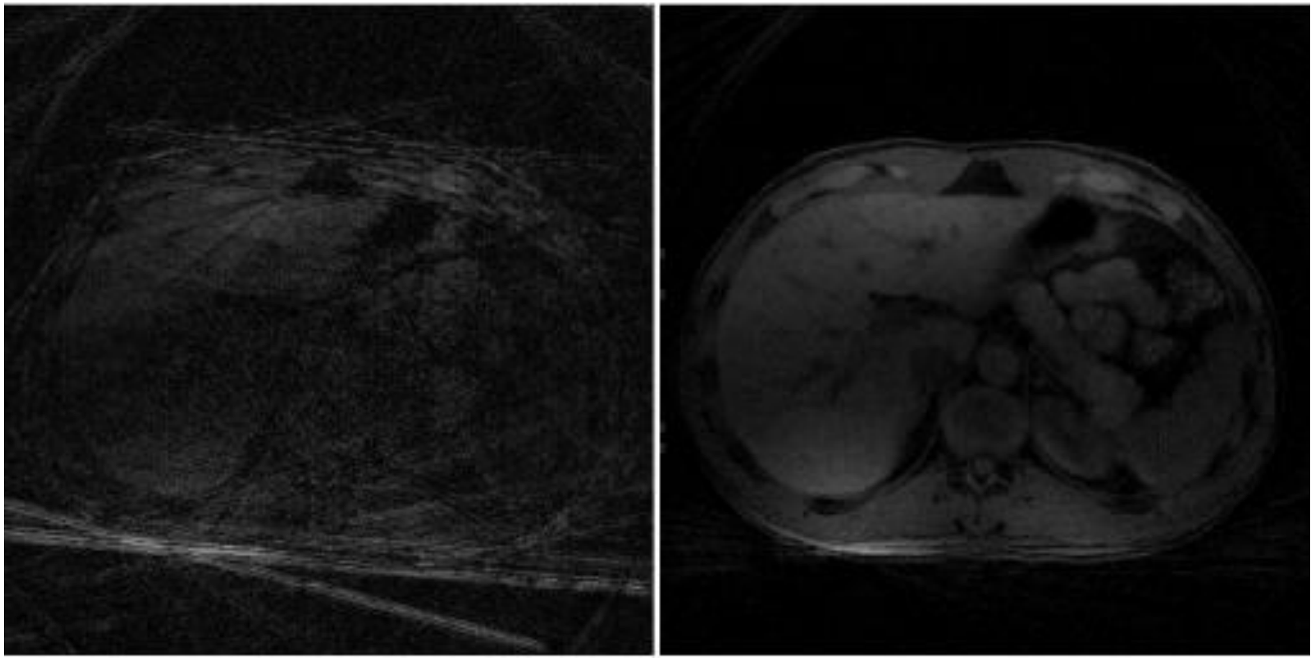


Dynamic Liver MRI

- 13 spokes/frame to reconstruct 400 spokes/frame

Conventional reconstruction

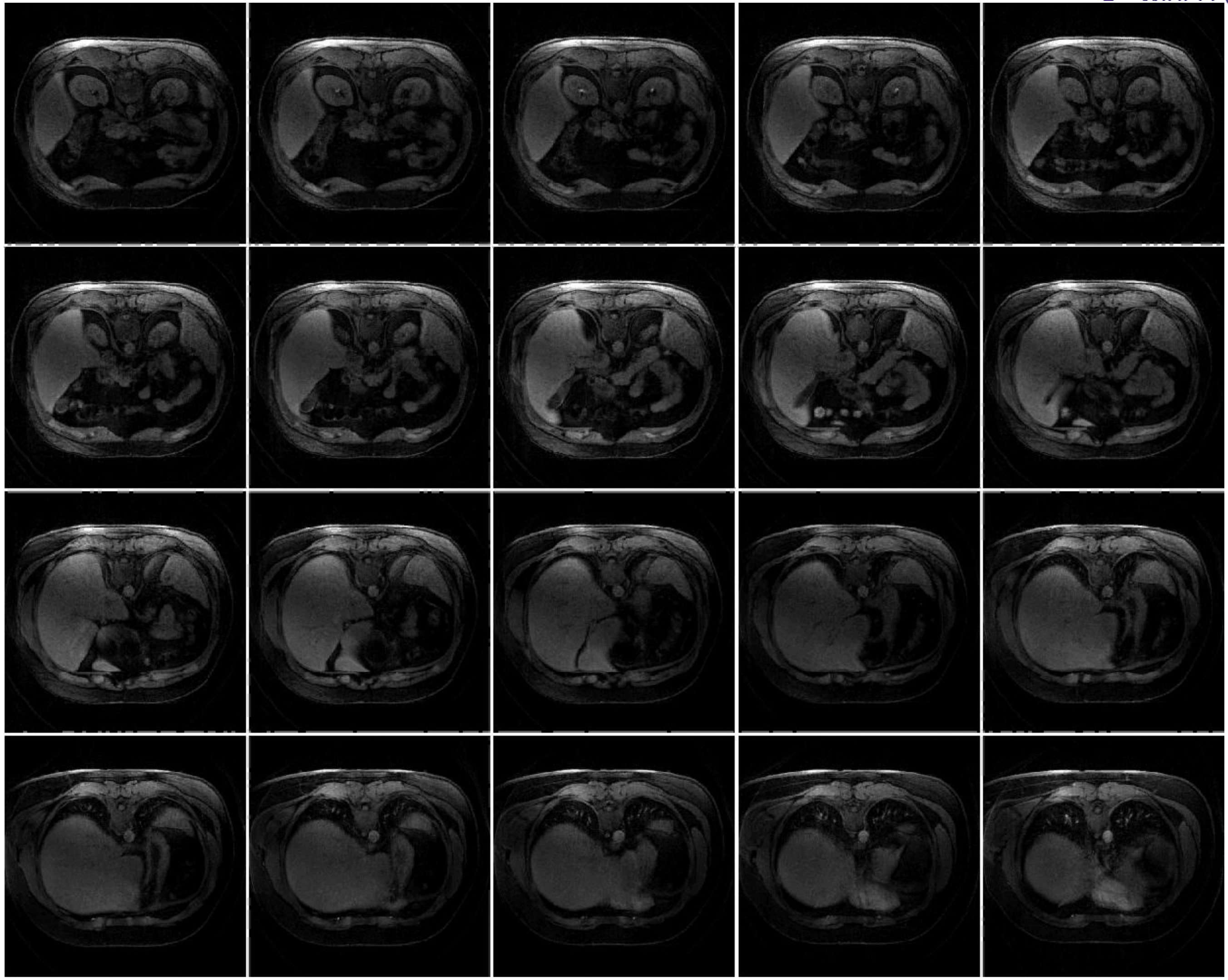
CS & PI



Feng L et al. Accepted for ISMRM 2012

Free-Breathing Dynamic Contrast-Enhanced Liver MRI

- 20-fold acceleration
- Whole-liver coverage (40 slices)
- Temporal resolution = 2.8 sec / volume
- Spatial resolution = $1x1x3mm^3$
- Image matrix = 256x256x40

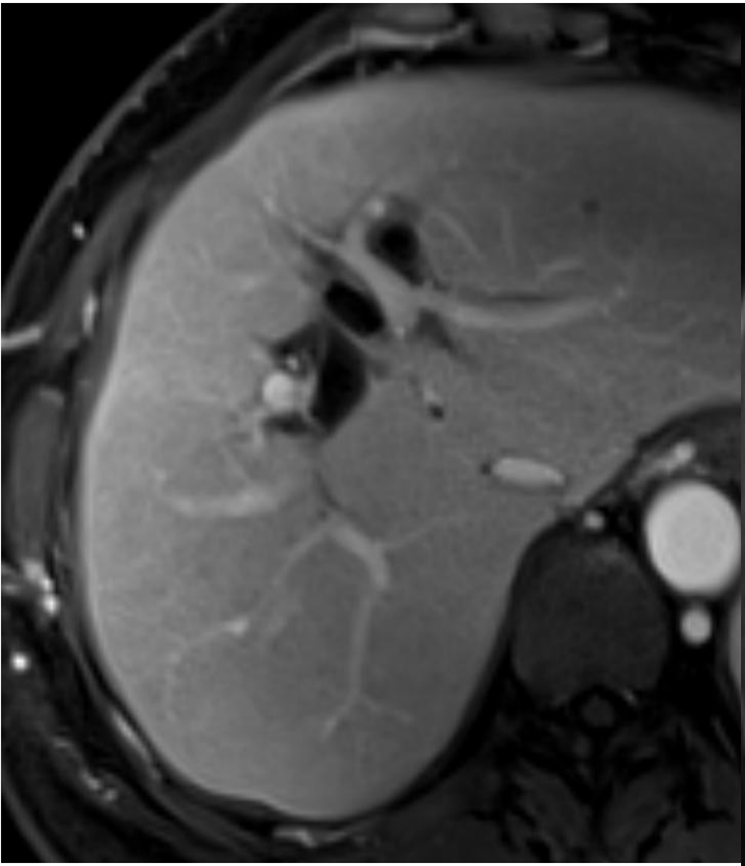


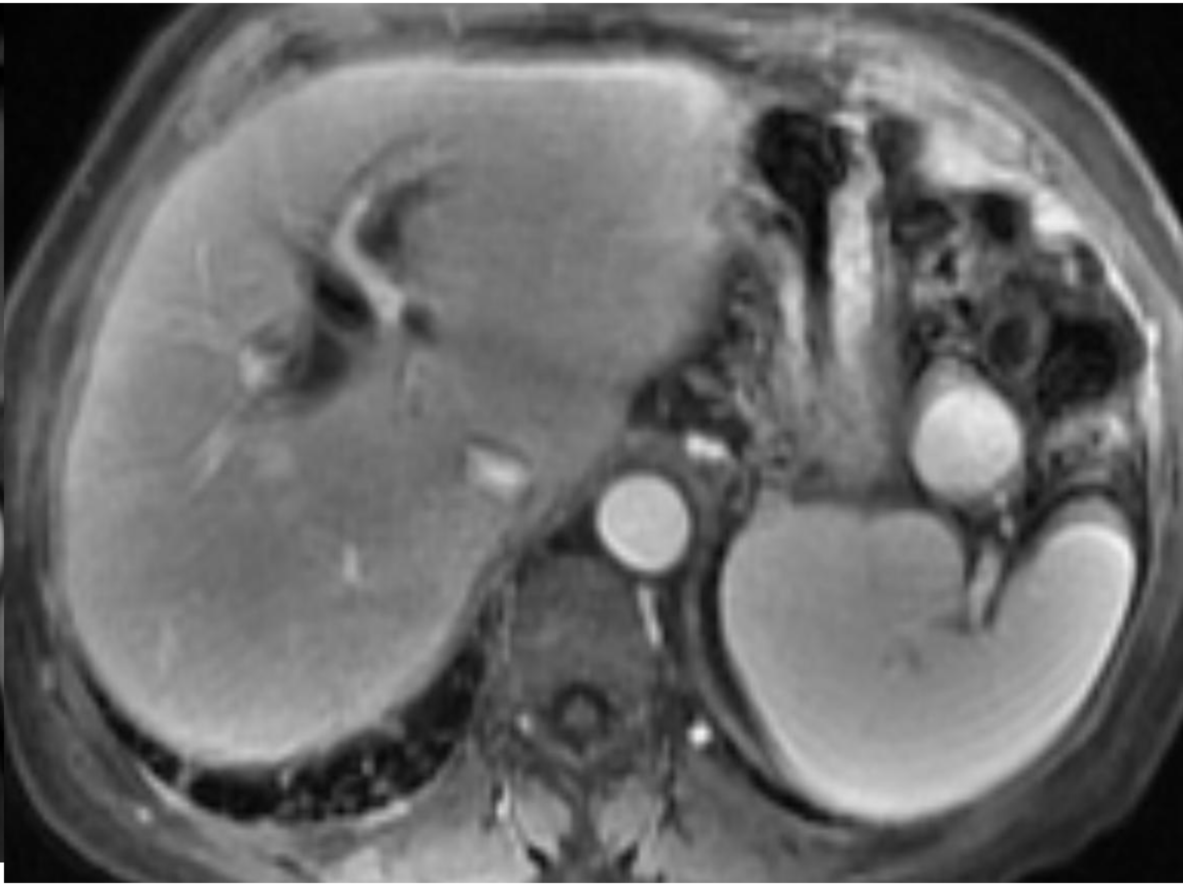
Feng L et al. Accepted for ISMRM 2012

Free-Breathing High-Resolution Liver MRI

Accelerated free-breathing scan (384x384 matrix)

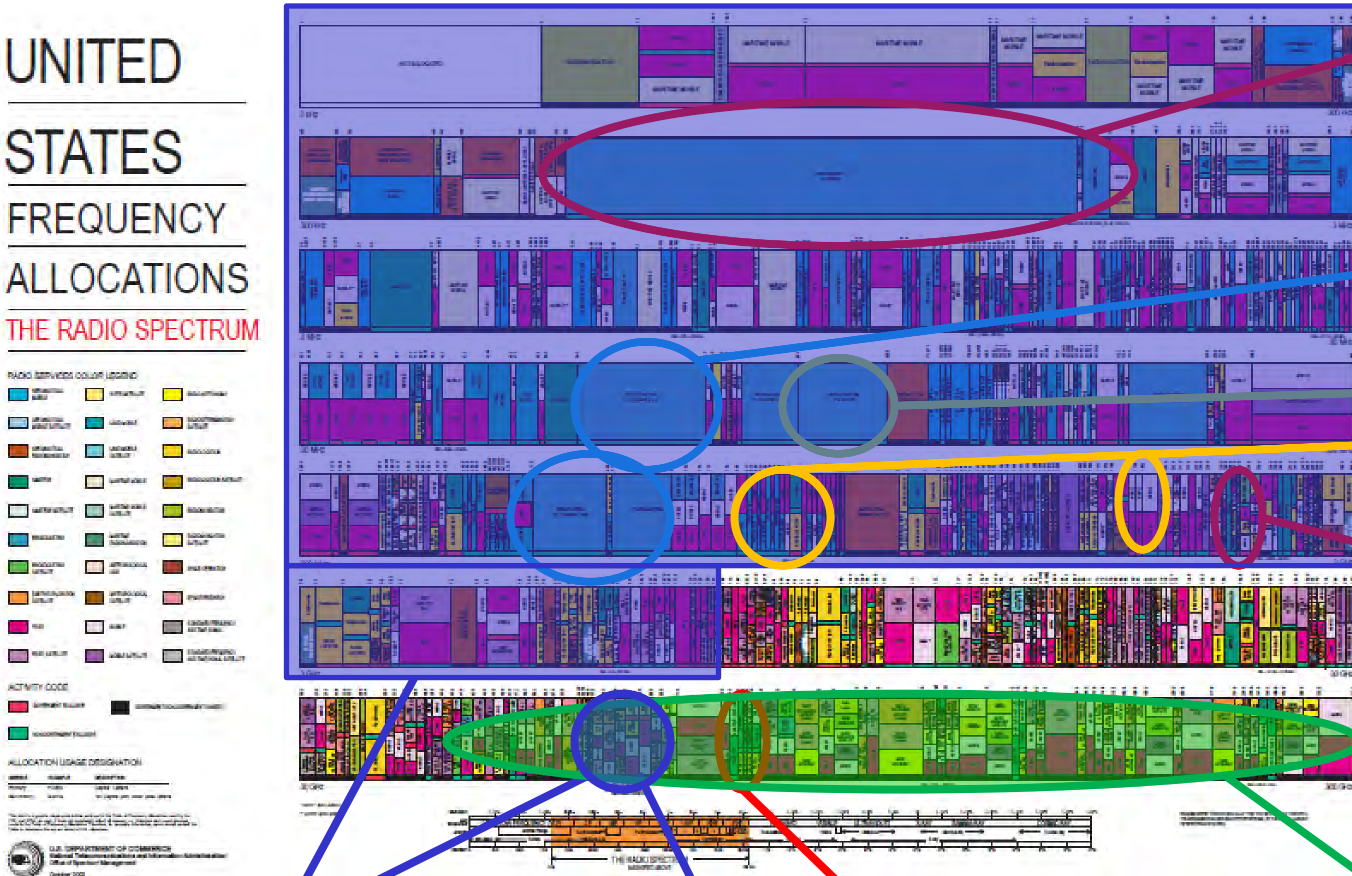
Conventional breath-held scan (256x256 matrix)





Chandarana H et al. Accepted for ISMRM 2012

Spectrum = real estate



AM Radio

TV Broadcast

FM Radio

Cellular

Wi-Fi

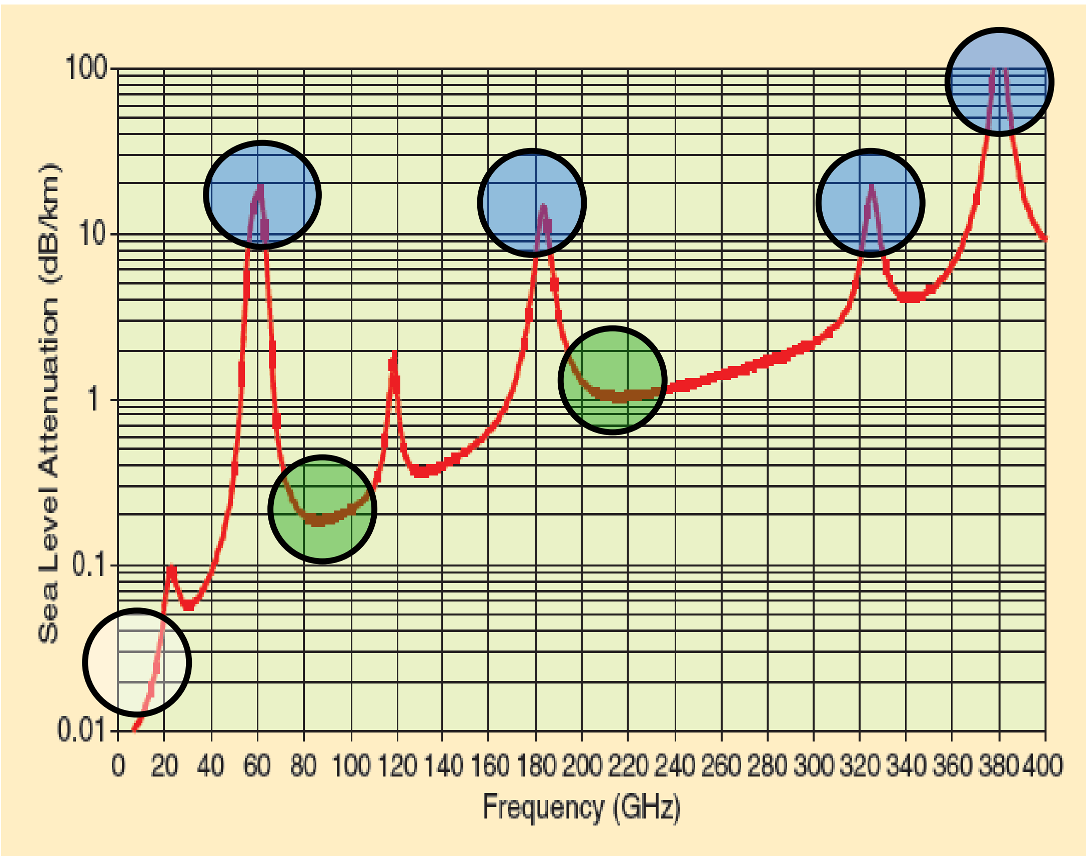
Active CMOS IC Research

77GHz Vehicular Radar

60GHz Spectrum

Shaded Areas = Equivalent Spectrum!

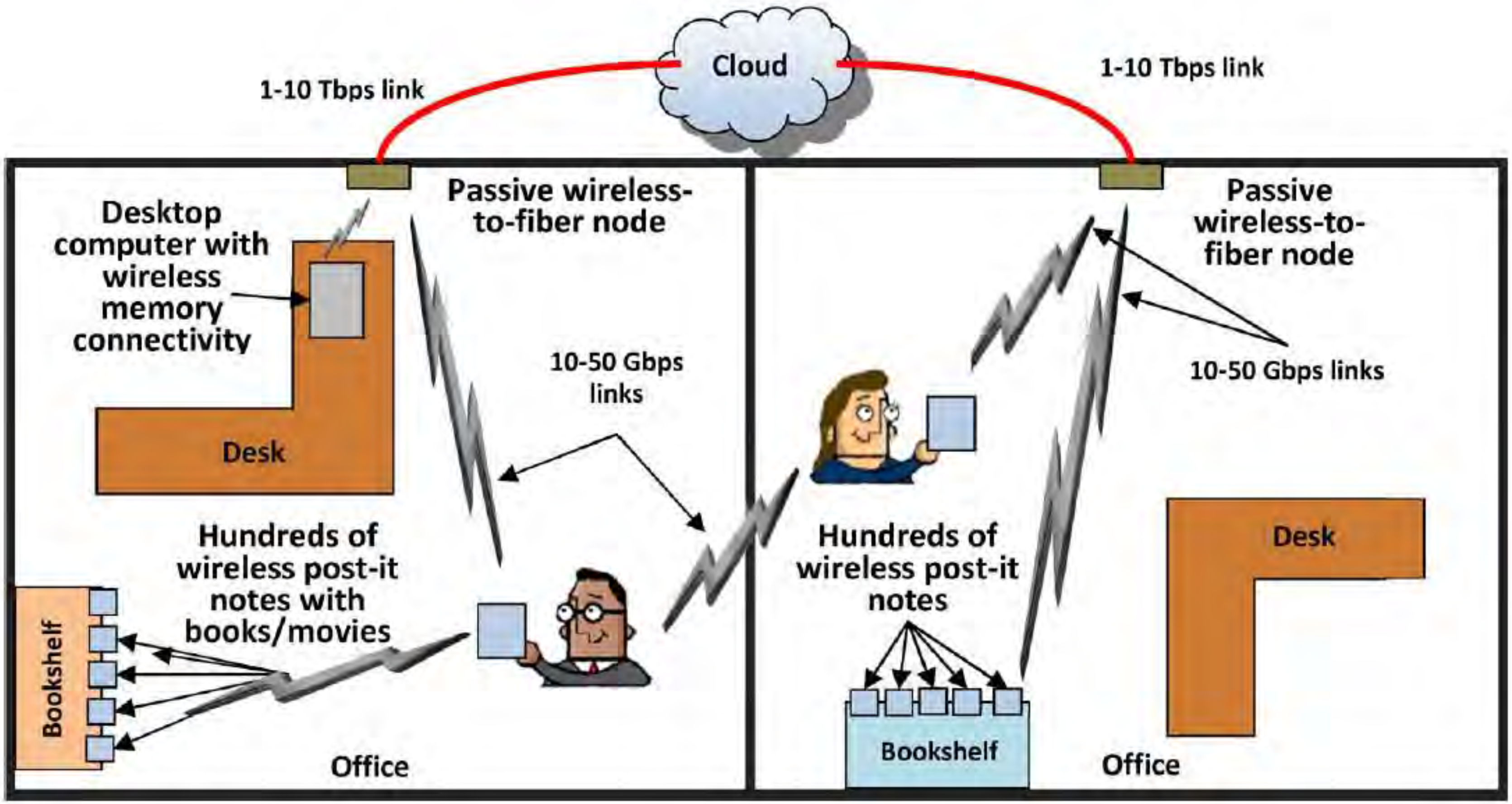
60 GHz and Above (sub-THz)
Important Short and Long Range Applications



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”

Office of the future



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.

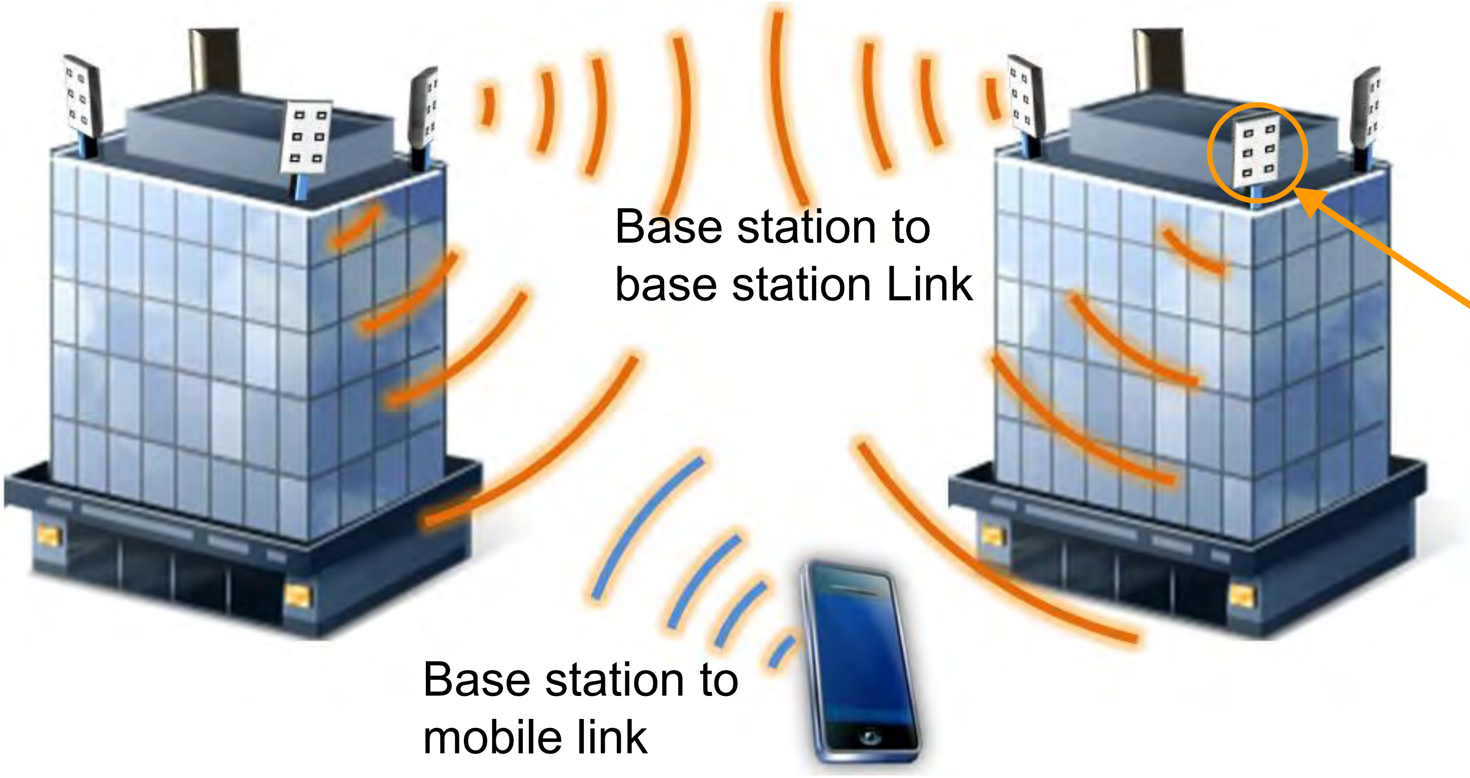
Cellular and Wireless Backhaul

Trends:

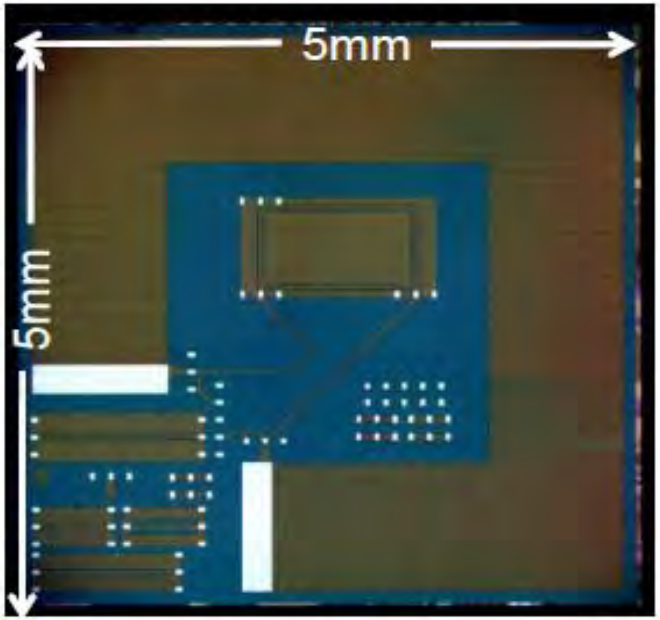
- Higher data usage
- Increase in base station density (femto/pico cells)
- Greater frequency reuse

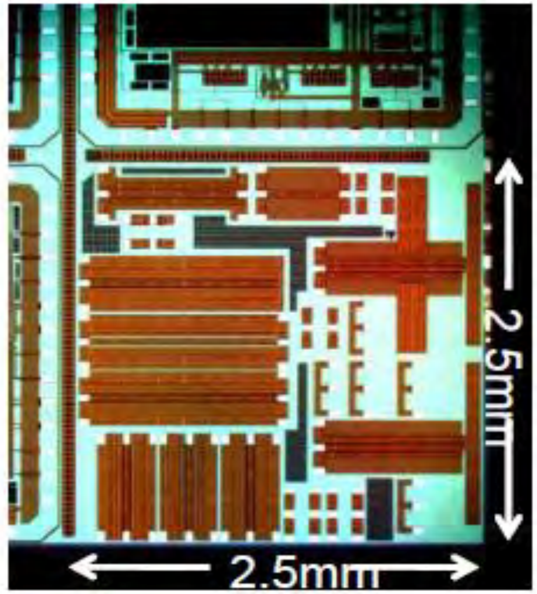
Problem: fiber optic backhaul is expensive and difficult to install.

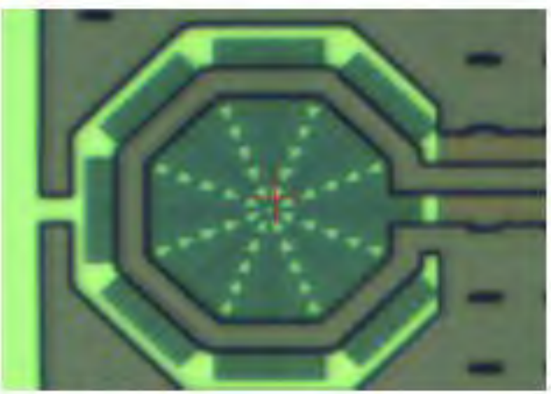
Solution: Cheap CMOS-based wireless backhaul with beam steering capability.

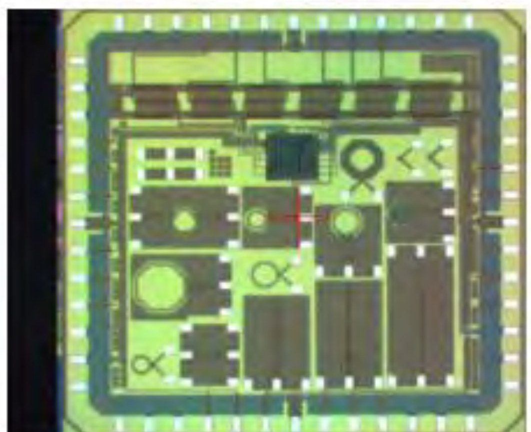


mmWave On-Chip Die Photos







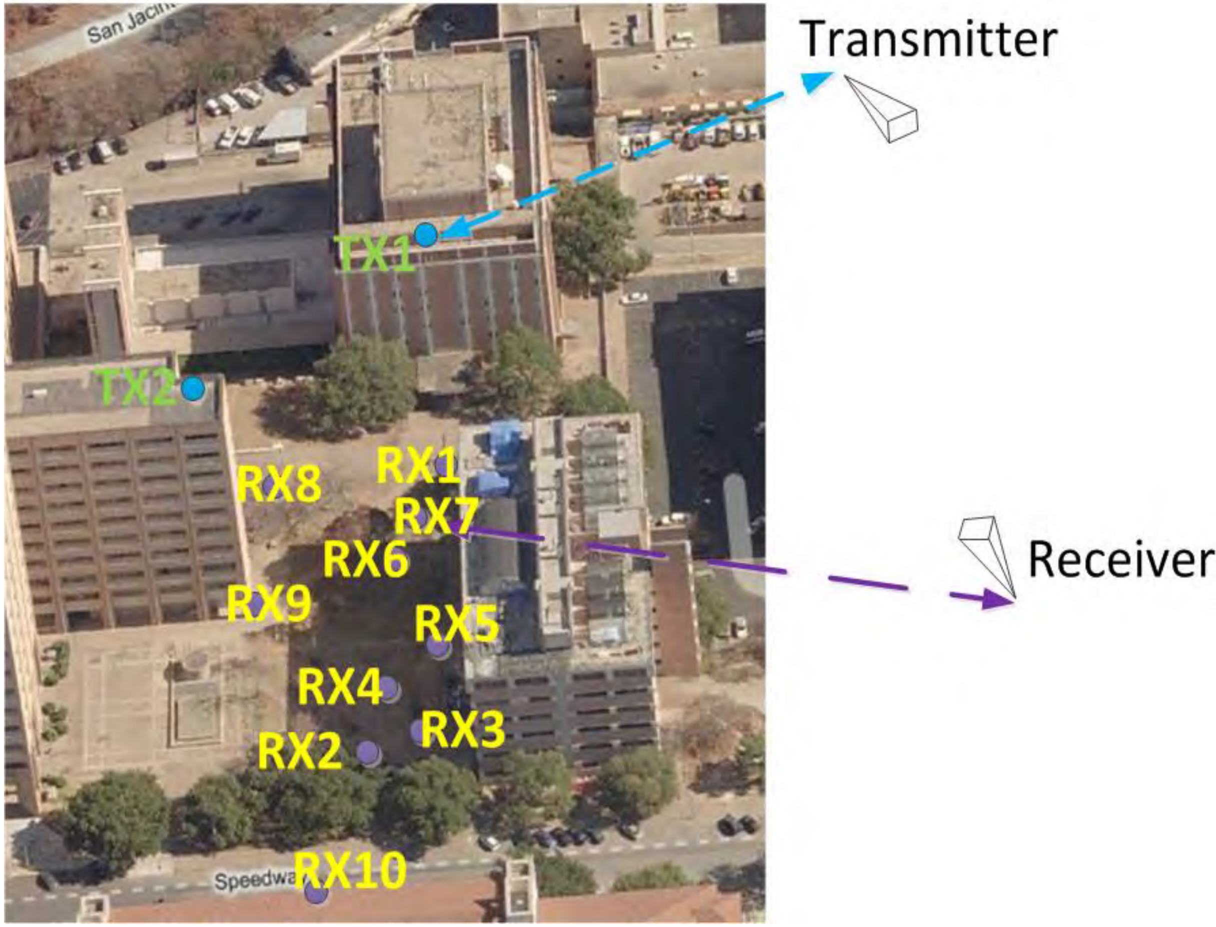


- Close relationship with fabrication company
- Several chips fabricated in ’08-’11
- Collaborative die among several UT-ECE faculty/students
- mmWave on-chip antennas
  - Yagi
  - Dipole
- mmWave transmission lines/ inductors
- PN Correlators for channel sounding

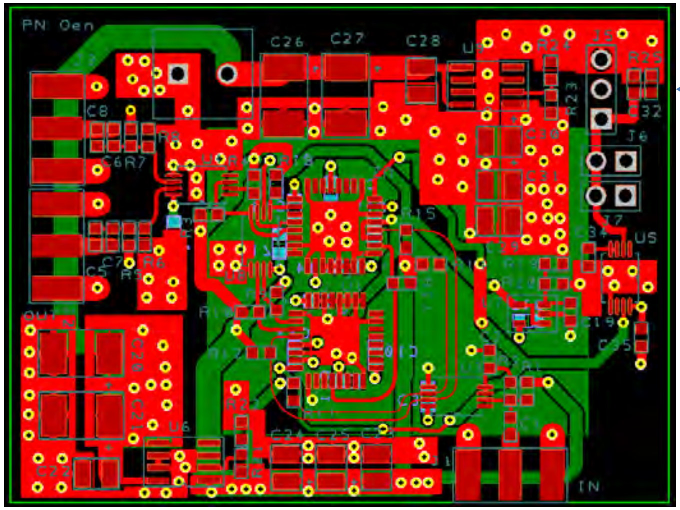
F. Gutierrez, S. Agarwal, K. Parrish, T. S. Rappaport, “On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems,” *IEEE Journal on Selected Areas in Communications*, Vol. 27, Issue 8, October 2009, pp. 1367-1378. Also see “Challenges and approaches to on-chip millimeter wave antenna pattern measurements,” IEEE Microwave Symposium Digest (MTT), Baltimore, MD, June 5, 2011

5G Cellular Measurements 38 GHz and 60 GHz

- Move the transmitter to various building rooftop locations (e.g. TX1 and TX2)
- For each transmitter location, move the receiver to various locations, (e.g. RX 1 – 10) and measure the channel w/varying antenna angles.
- Use the collected results to generate statistical channel models



Channel Sounder Sliding Correlator Hardware



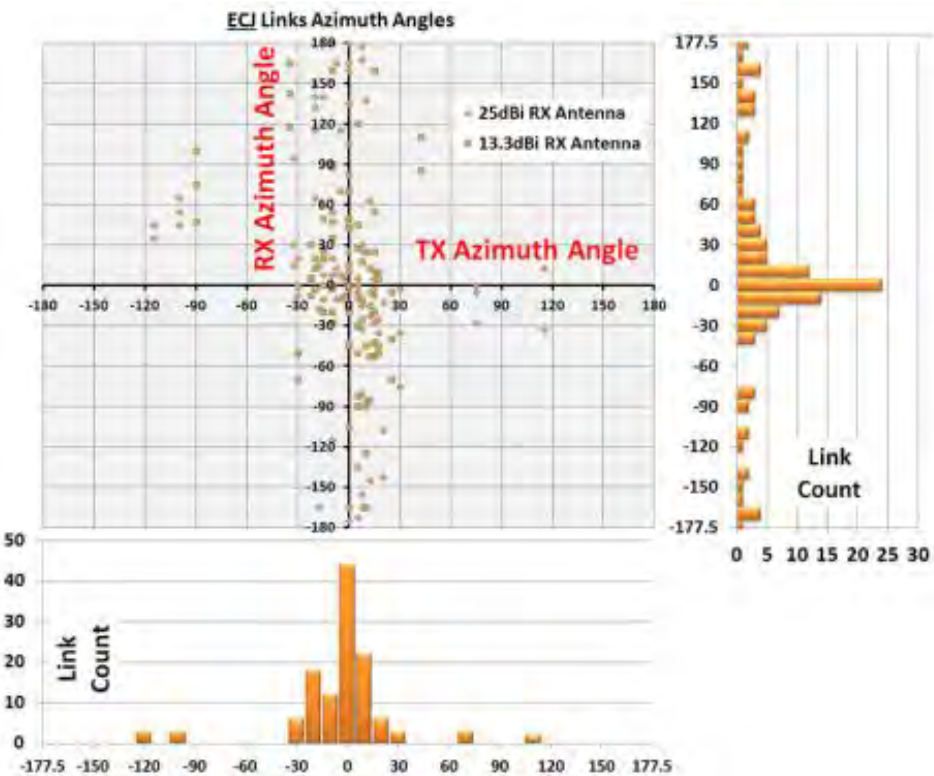
Pseudorandom Noise (PN) Generator

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

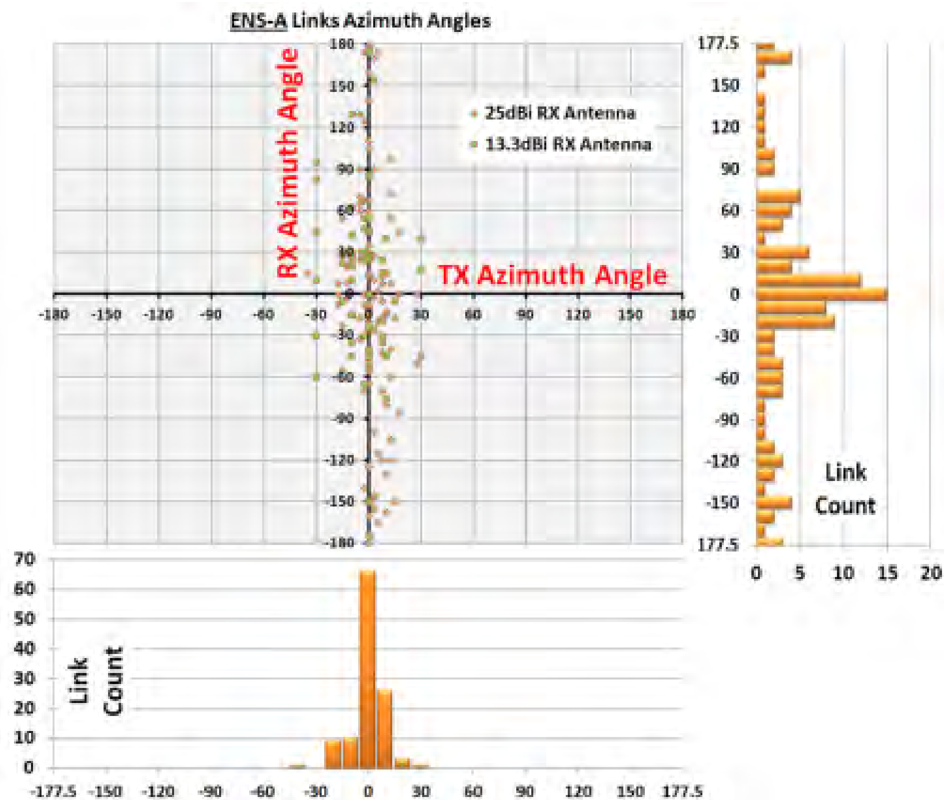
Upconverter and Downconverter assemblies at 38 and 60 GHz, newer ones built at 28 GHz, 72 GHz

38 GHz Cellular AOA

TX height 8m above ground



TX height 36m above ground

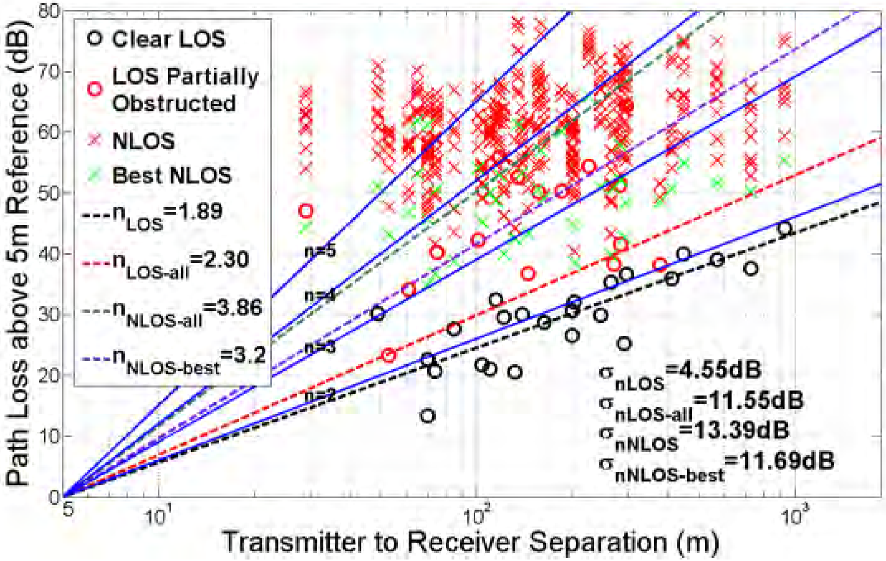


- TX angle spread is small but increases at low TX heights
- Receiver spread is heavily dependent on environment

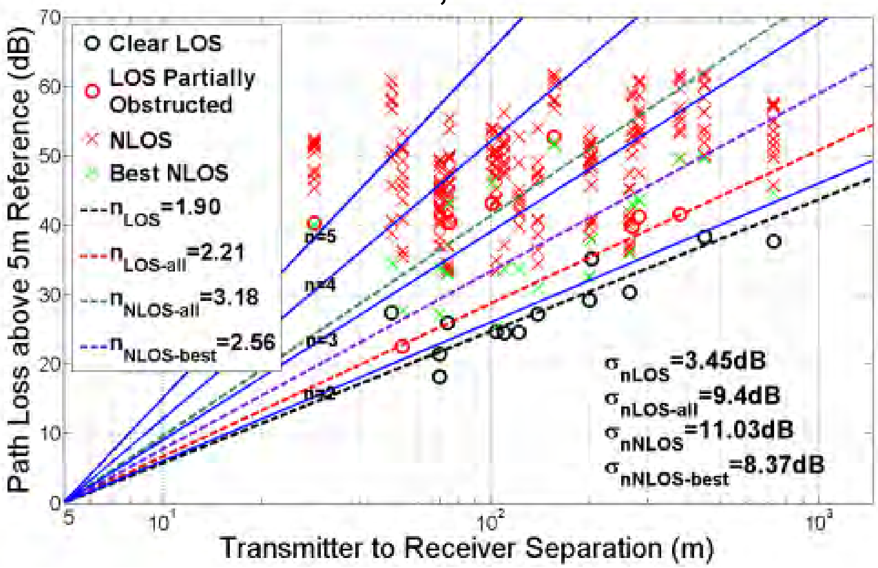
T. S. Rappaport, E. Ben-Dor, J. N. Murdock, Y. Qiao, "38 GHz and 60 GHz Angle-Dependent Propagation for Cellular & Peer-to-Peer Wireless Communications," IEEE International Conference on Communications (ICC 2012), June 2012.

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)

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.


NYU
100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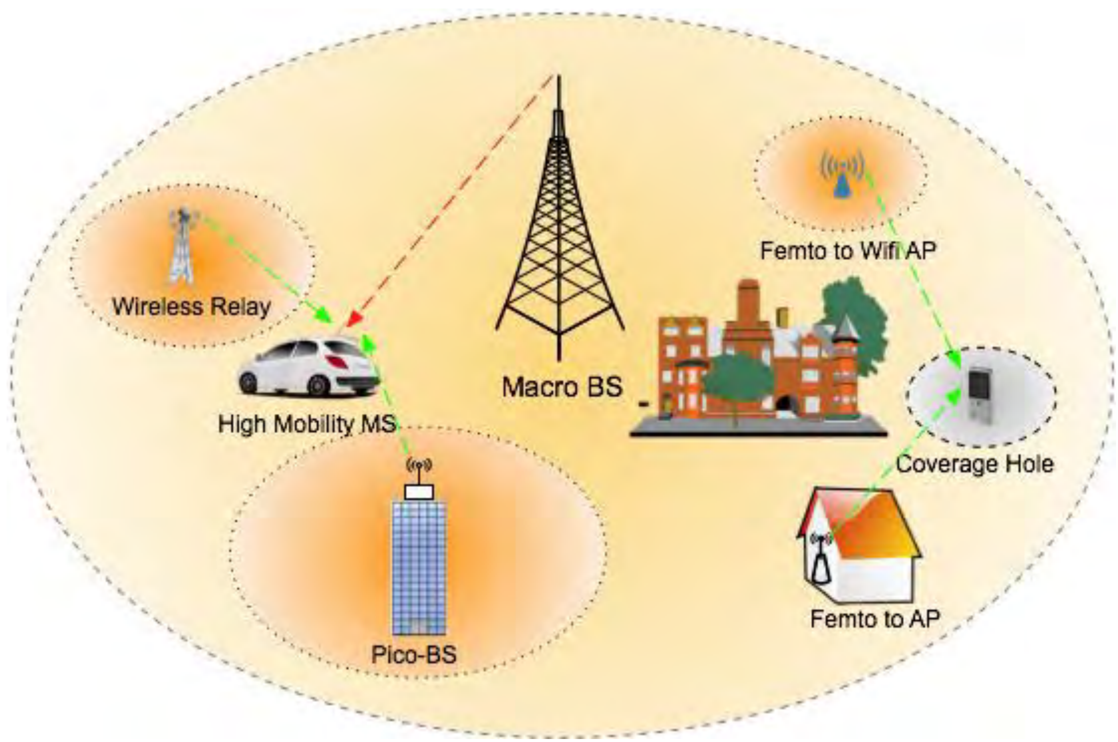
Cooperative MIMO for Het Nets

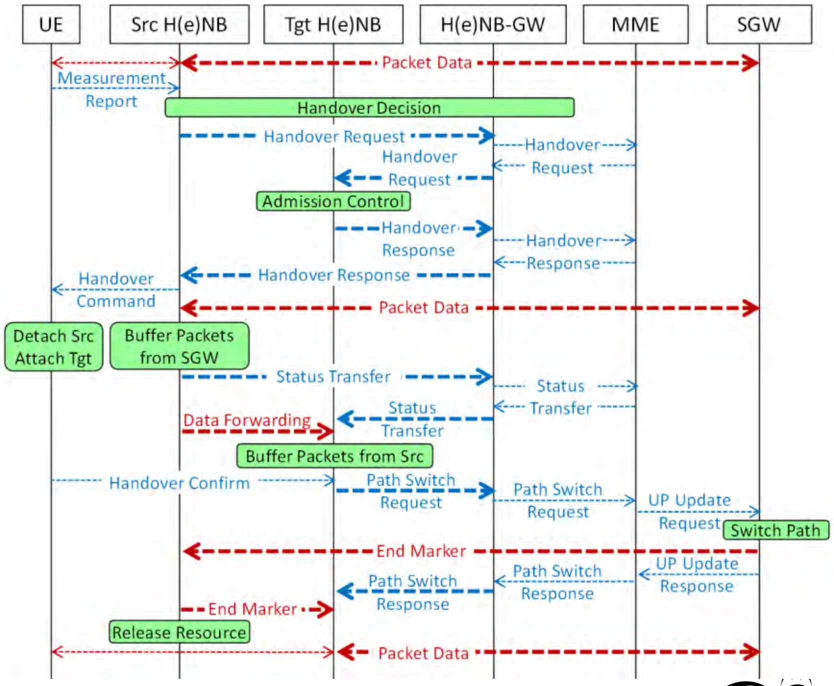
- For high mobility MSs or MSs that have not been covered by any femtocell, cooperative MIMO
  – enables fully *opportunistic* use of all available surrounding radios.
  – increases network capacity and helps to reduce coverage holes.



Fast Handover with Femtocells

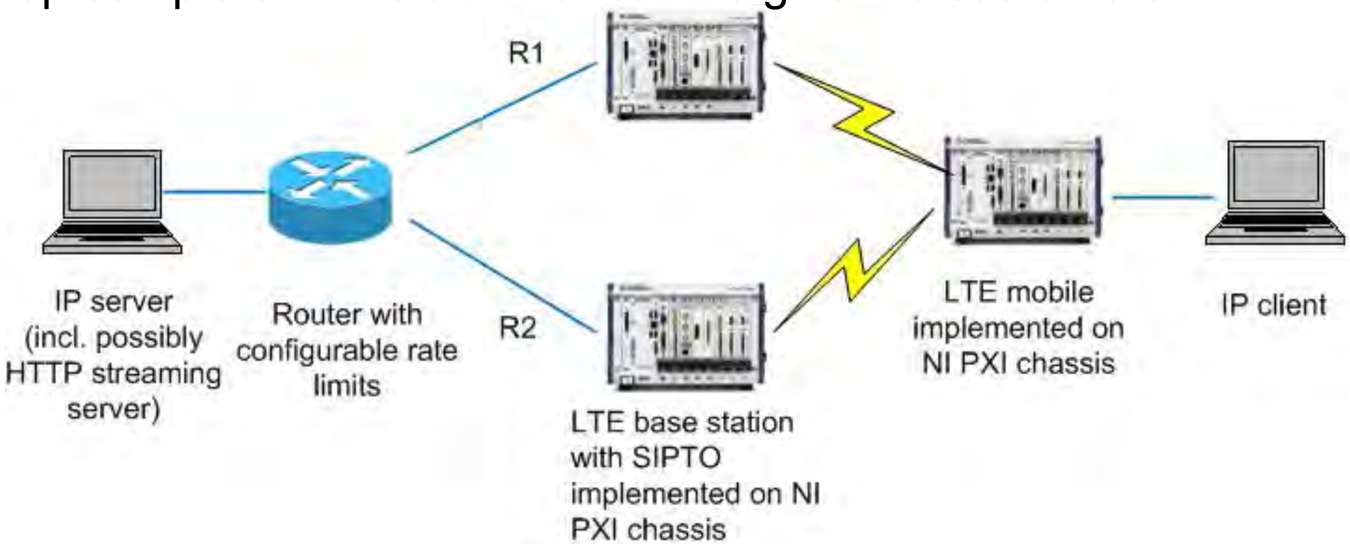
- Legacy Handover in Femtocells for Mobile Users:
  - Smaller cell size – More Frequent Handover.
  - Higher latency backhaul – Slower Handover.
  - Longer and more frequent interruptions on App layer.
  - Missed handover opportunities into passing Femtocells.

- Issues with Legacy Handover procedure:
  - Preparation for Handoff, the Handoff and Post-Handoff processes are tightly coupled.
  - Long time gap between Handover Decision and actual Handoff.
  - Forwarding of data over the internet from source to target Femtocell during Handover.

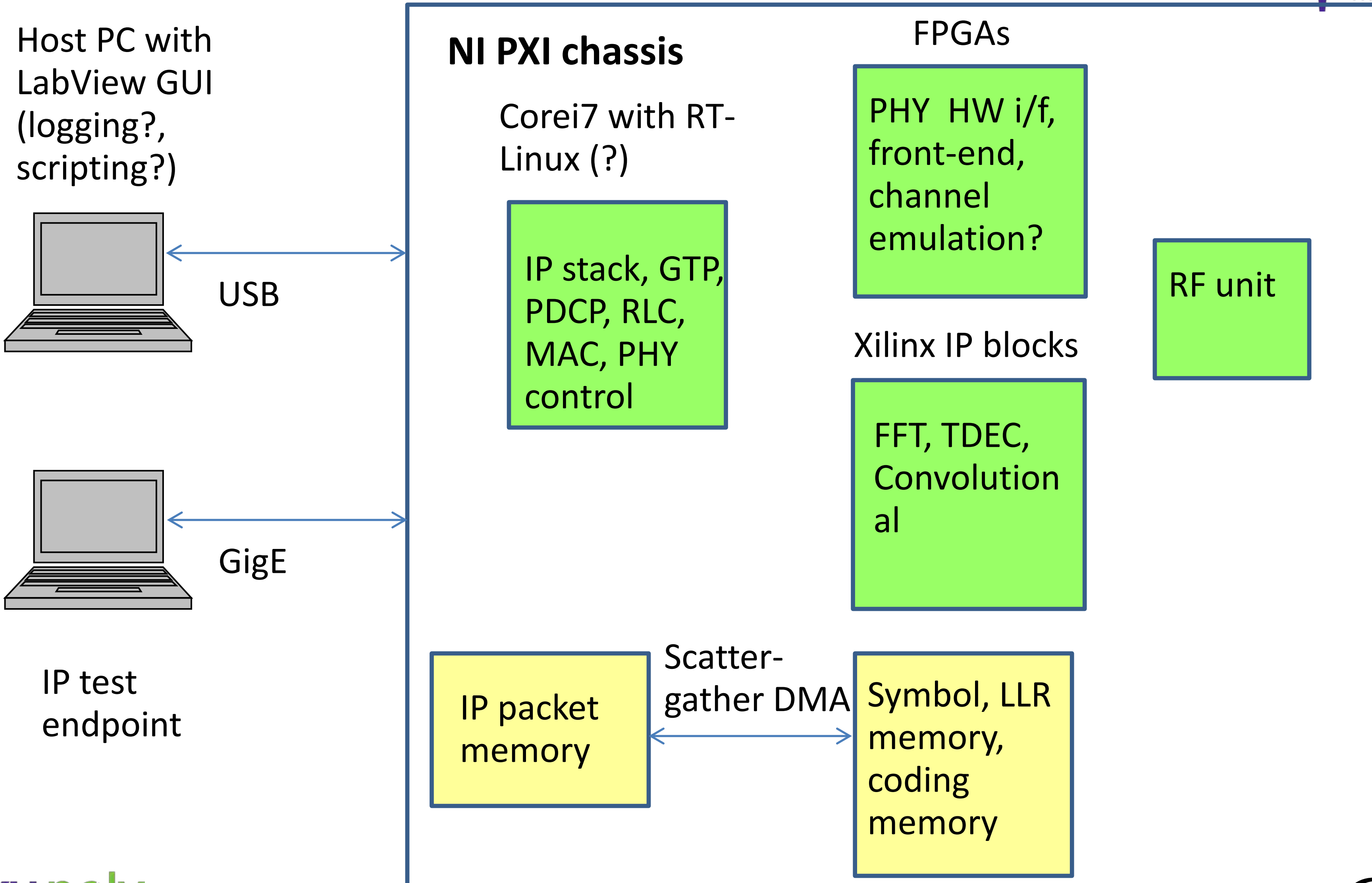


Current National Instruments Projects

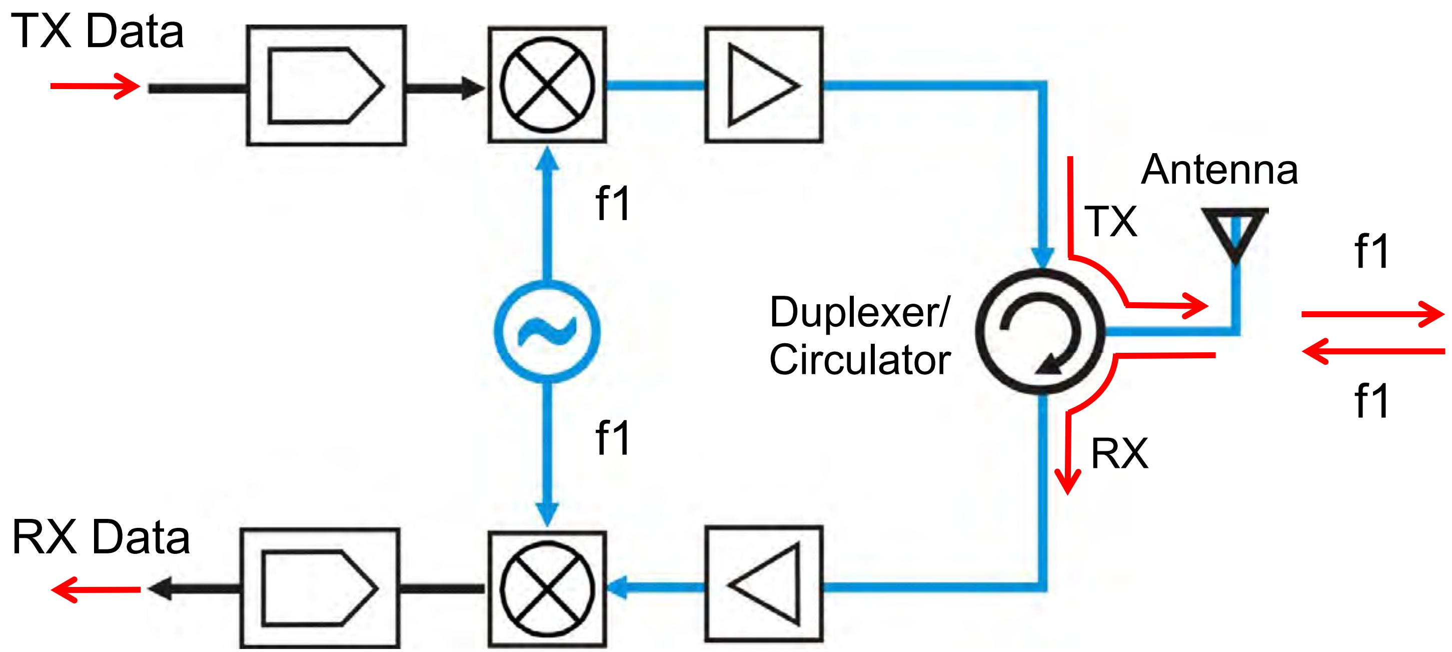
- Upper-layer algorithm experimentation for LTE-Advanced
  - Intercell interference coordination, cell selection, multiflow, …
- Benefits to NI:
  - Validate NI platform for high-throughput cellular systems
  - Develop complete LTE stack that can be given to customers



Partitioning on NI Platform



Full Duplex using Common Carrier



- *Theoretically achieve 2x system capacity*
- *Eliminate hidden terminal problem*
- *Low Latency and Fairness*
- *More efficient MAC designs*

Single Antenna Prototype

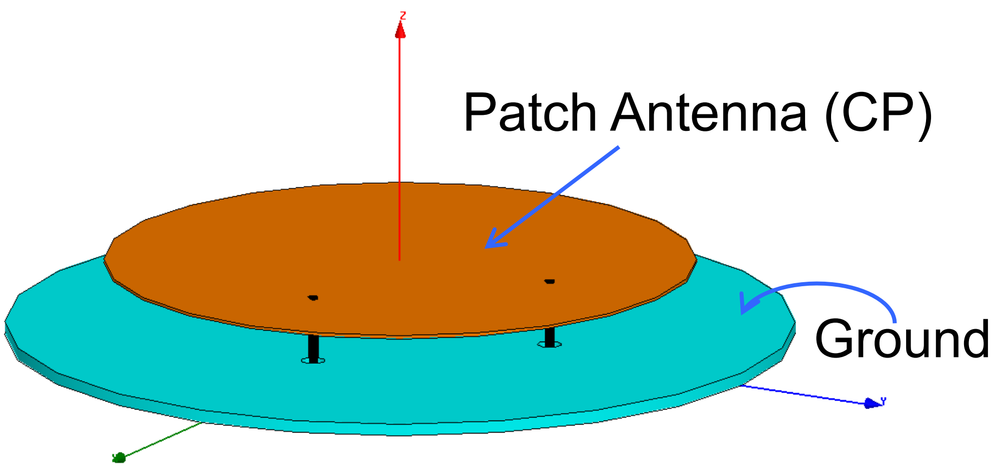


Photo of complete antenna

Assembly Diagram

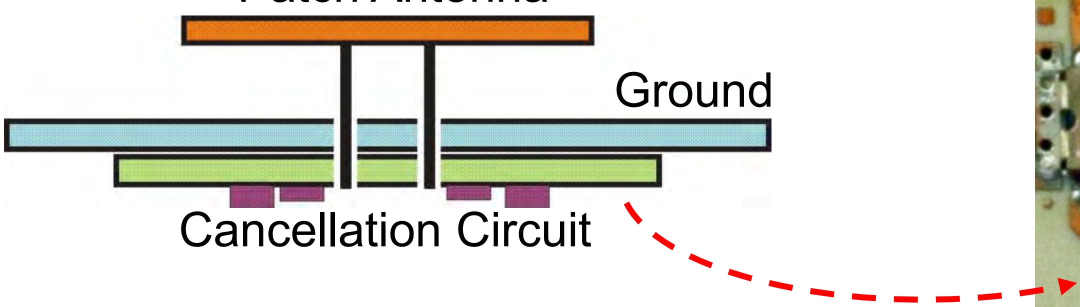
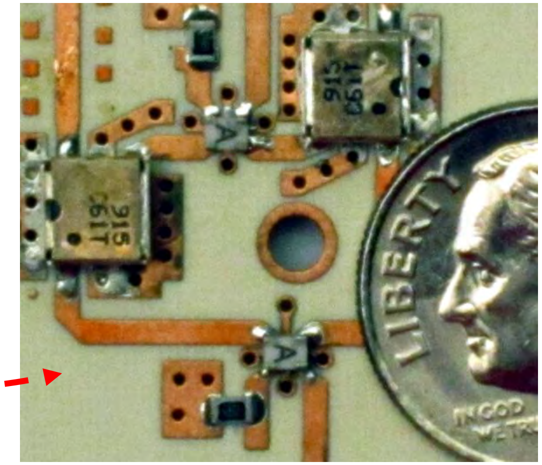


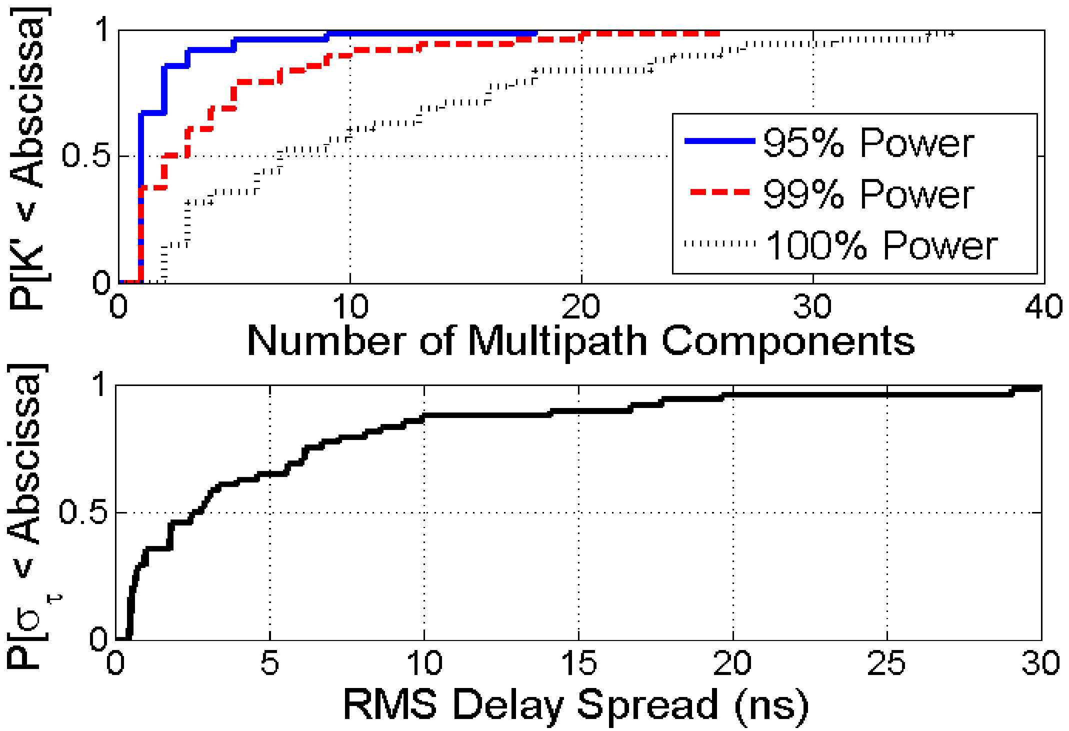
Photo of Cancellation Circuit



Patent pending

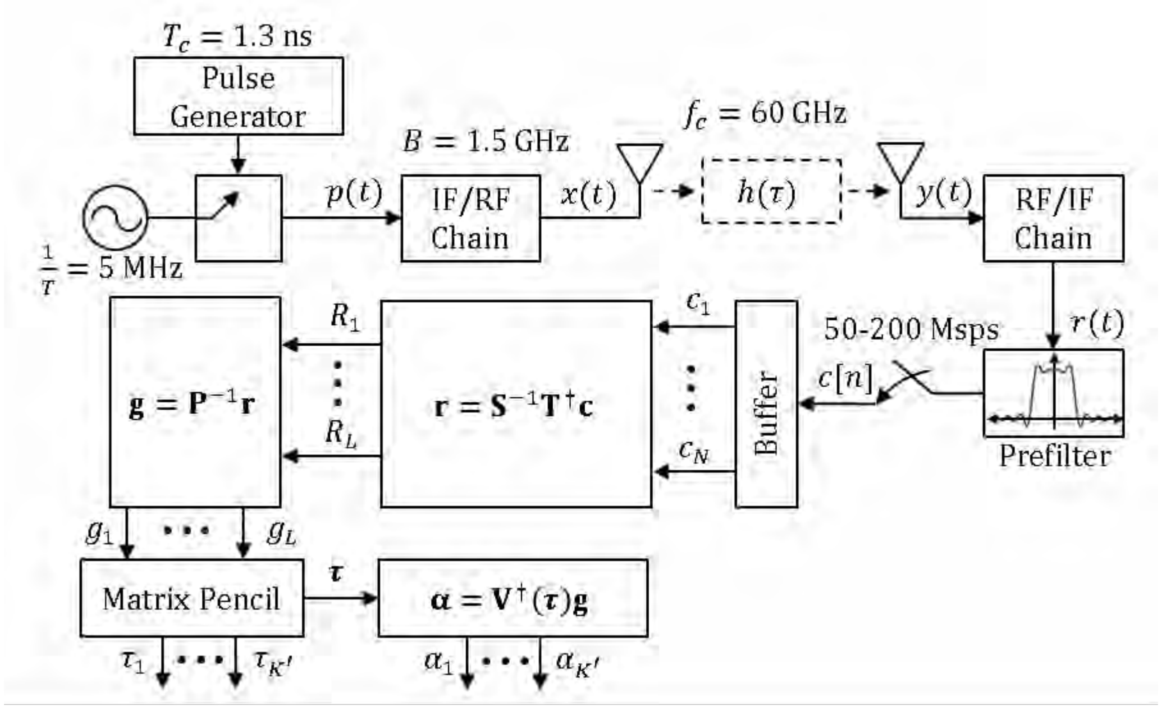
Millimeter Wave Channel Sparsity

- CDFs of (a) channel sparsity and (b) RMS delay spread for 60 GHz outdoor peer-to-peer measurements
- 95% signal power in first peaks



Future Work using Compressed Sensing for Channel Sounding

- Incorporate *angle of arrival* (adaptive beam forming)
- Build ***Massively Broadband Channel Sounding Xampler***



Shims

- Semantically consistent method for adding network functionality
  - Works with legacy applications!
- Often improve latency, bandwidth, loss rate, etc. by a factor of two!
- Easy to code
- Low overhead

Without FEC

With FEC shim

Seattle Testbed summary

Seattle testbed

- Real system deployed on about 10K computers
  - Geographic diversity, network diversity, device diversity...
  - Laptops, desktops, tablets, phones
- Battle tested educational platform!
  - Used in 24 classes
  - Networking, security, OS
- Interesting research problems
  - Write-Once Run Anywhere
  - Network Heterogeneity
  - Legacy cloud containers (SFI meets Seattle VM)

Open for public use

https://seattle.cs.washington.edu/

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