The Renaissance of Wireless Communications in the Massively Broadband ® Era

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Polytechnic Institute of New York University

IEEE Vehicular Technology Conference Plenary
September 5, 2012
• Spectrum = real estate

United States Frequency Allocations
The Radio Spectrum

AM Radio
FM Radio
TV Broadcast
Cellular
Wi-Fi
60GHz Spectrum
77GHz Vehicular Radar
Active CMOS IC Research
Shaded Areas = Equivalent Spectrum!

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

- 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”


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Spectrum Allocation History for 60GHz – Key mmWave Frequency Band

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

**Figure 1** International unlicensed spectrum around 60 GHz.

mmWave Wavelength Visualization – 60GHz

5 millimeters

Integrated Circuit
mmWave and CMOS

- 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

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

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.

- Base station to base station Link
- Base station to mobile link
- Antenna array
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

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

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### mmWave 60 GHz Link Budget

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

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

Beam Forming and Steering

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

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.

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Why On-Chip Antennas?

- Millimeter-Wave (mmWave) and THz signals have small wavelengths ($\lambda$)
  - Wavelength of mmWave Frequencies fit On-Chip!
- If immersed in dielectric, $\lambda$ shrinks by $\sqrt{\text{permittivity}}$
  - Example: permittivity of SiO$_2$ $\approx$ 4 $\Rightarrow$ wavelength in SiO$_2$ $\approx$ 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

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.

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

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

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)

## Antenna Topologies - Comparison

### Summary of Results

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Max Gain</th>
<th>Horizontal Gain</th>
<th>Θ of Max Gain*</th>
<th>Efficiency</th>
<th>F/B</th>
<th>Approximate Area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antennas developed in this paper</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipole</td>
<td>-7.3 dBi</td>
<td>-7.3 dBi</td>
<td>0°</td>
<td>9%</td>
<td>3 dB</td>
<td>0.13 mm²</td>
</tr>
<tr>
<td>Yagi</td>
<td>-3.55 dBi</td>
<td>-3.8 dBi</td>
<td>20°</td>
<td>15.8%</td>
<td>10.4 dB</td>
<td>0.9 mm² (including spacing)</td>
</tr>
<tr>
<td>Rhombic</td>
<td>-0.2 dBi</td>
<td>-1.27 dBi</td>
<td>39°</td>
<td>85%</td>
<td>3.7 dB</td>
<td>3.5 mm² (metal only)</td>
</tr>
<tr>
<td><strong>Past works</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quasi-Yagi</td>
<td>-12.5 dBi</td>
<td></td>
<td></td>
<td>5.6%</td>
<td>“Poor”</td>
<td></td>
</tr>
<tr>
<td>Inverted F</td>
<td>-19 dBi</td>
<td></td>
<td></td>
<td>3.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPW-Fed Yagi</td>
<td>-10 dBi</td>
<td></td>
<td></td>
<td>10%</td>
<td>9 dB</td>
<td></td>
</tr>
<tr>
<td>Triangle</td>
<td>-9.4 dBi</td>
<td></td>
<td></td>
<td>12%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


*above horizon
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 Fresnel zone
• Wind may modify link quality

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.

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

<table>
<thead>
<tr>
<th>Antenna Height</th>
<th>All Measurement Locations</th>
<th>&lt;3 km From Transmitter</th>
<th>&lt;2 km From Transmitter</th>
<th>&lt;1 km From Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.3 m</td>
<td>32%</td>
<td>32%</td>
<td>28%</td>
<td>14%</td>
</tr>
<tr>
<td>7.3 m</td>
<td>54%</td>
<td>55%</td>
<td>50%</td>
<td>29%</td>
</tr>
<tr>
<td>3.4, 4.0 m</td>
<td>74%</td>
<td>73%</td>
<td>70%</td>
<td>52%</td>
</tr>
</tbody>
</table>

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


Path loss is important to estimate SNR and CIR at receiver.

- Important in determining cell sizes.
- Log-normal shadowing model is most commonly used.

\[
PL = PL_0 + 10\log_{10}(d/d_0) + X_{\sigma}
\]

- \(PL_0\) is path loss measured at close-in distance \(d_0\).
- \(X_{\sigma}\) is a Gaussian random variable with standard deviation of \(\sigma\) that estimates the shadowing.

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

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

$$\tau_i = \text{Excess delay at time point } i$$

$$P_i = \text{Power at time point } i$$

RMS Delay Spread

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

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.

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
Radio propagation measurement results for 5G cellular

P2P and cellular outdoor at 38 and 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° 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° BW TX antenna and 8° or 49°(13.3dBi gain) RX antenna.
  - ~half of locations measured with 49° ant.
  - LOS, partially-obstructed LOS, and NLOS links
  - Outage Study – likelihood of outage
    - Two TX locations of 18 and 36m height.
    - 8° BW antennas
    - 53 random RX locations
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

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

Histogram of RX 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 Path Loss, 25dBi 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

### 38 GHz Cellular Path Loss

<table>
<thead>
<tr>
<th></th>
<th>25dBi RX Ant.</th>
<th>13.3dBi RX Ant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS Path Loss</td>
<td>2.30 (clear 1.90)</td>
<td>3.86 (best: 3.20)</td>
</tr>
<tr>
<td>NLOS Path Loss</td>
<td>9.44 dB</td>
<td>11.03 dB</td>
</tr>
<tr>
<td>LOS Path Loss Exponent</td>
<td>1.90</td>
<td>3.20</td>
</tr>
<tr>
<td>NLOS Path Loss Exponent</td>
<td>2.21</td>
<td>2.56</td>
</tr>
<tr>
<td>Path Loss std. dev. (dB)</td>
<td>11.6 (clear 4.6)</td>
<td>13.4 (best 11.7)</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Transmitter Location</th>
<th>Height</th>
<th>% Outage with &gt;160 dB PL</th>
<th>% Outage with &gt;150 dB PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX 1 ENS</td>
<td>36 m</td>
<td>18.9% all, 0% &lt; 200 m</td>
<td>52.8% all, 27.3 % &lt; 200 m</td>
</tr>
<tr>
<td>TX 2 WRW</td>
<td>18 m</td>
<td>39.6% all, 0% &lt; 200 m</td>
<td>52.8% all, 10% &lt; 200 m</td>
</tr>
</tbody>
</table>

**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
Millimeter Wave Measurements in NYC

RX location: RX9 (Othmer Residence Hall, NYU-Poly, Brooklyn, New York)

TX location: ROG1 (Rogers Hall, NYU-Poly, Brooklyn, New York)
28 GHz LOS in Brooklyn

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

- Configuration 9
- Line of Sight
- 32 m TR separation
- $\sigma_t = 0.83$ ns
- $PL_{rel-5m} = 36.92$ dB
- $TX_{AZ/EL} = 5^\circ/10^\circ$
- $RX_{AZ/EL} = -100^\circ/20^\circ$
- $\tau_{max 10 \, dB} = 4.25$ ns
- $\tau_{max 20 \, dB} = 4.9375$ ns
28 GHz LOS in Brooklyn

COL 1 : RX 1

Configuration 2
Line of Sight
32 m TR separation
$\sigma_t = 16.33\text{ns}$
$PL_{\text{rel-5m}} = 53.48\text{dB}$

TX $_{\text{AZ/EL}}$: $-5^\circ$ / $-10^\circ$
RX $_{\text{AZ/EL}}$: $120^\circ$ / $-20^\circ$

$\tau_{\text{max 10 dB}}: 52.9375\text{ ns}$
$\tau_{\text{max 20 dB}}: 94.4375\text{ ns}$

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

• Diffraction study with 25 dBi antennas

• TX and RX pointing at a glass door of building

<table>
<thead>
<tr>
<th>Received Power (dBm/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-80</td>
</tr>
<tr>
<td>-75</td>
</tr>
<tr>
<td>-70</td>
</tr>
<tr>
<td>-65</td>
</tr>
<tr>
<td>-60</td>
</tr>
<tr>
<td>-55</td>
</tr>
<tr>
<td>-50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Excess Delay (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>120</td>
</tr>
<tr>
<td>140</td>
</tr>
</tbody>
</table>

Configuration 8
Highly Obstructed
61 m TR separation

$\sigma_\tau = 12.74\text{ns}$

$P_{L_{rel-5m}} = 69.23\text{dB}$

$TX_{AZ/EL}: 5^\circ/-10^\circ$

$RX_{AZ/EL}: 60^\circ/-20^\circ$

$\tau_{max 10\text{dB}}: 17.1875\text{ ns}$

$\tau_{max 20\text{dB}}: 88.1875\text{ ns}$
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

• 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


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So.....how does Wireless Communications enter its Renaissance?
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
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
NYU WIRELESS Industrial Affiliates

- National Instruments
- Samsung
- 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?
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

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 (↑FiO₂)

- **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 (↑PaCO₂)

- **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.
“State of the Art” Clinical Electrode Arrays

- 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 Active 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

Electrode on Brain

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
Recent Publications related to this Work


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


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