Massive MIMO and Beyond: Innovation in the Wireless Physical Layer

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RADIO CLUB OF AMERICA ANNUAL TECHNICAL SYMPOSIUM
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• Collectively serve as a trusted, knowledgeable, and valued thought leader for our Industrial Affiliate companies and the global wireless industry

• Provide a fervent research and educational environment for our students, so they may be highly productive throughout their careers, both during and after their time at NYU WIRELESS

• Provide high impact for NYU through our students, education, research, service, and collaborations with our Industrial Affiliates, governmental entities, and peers
To promote our Industrial Affiliates, students and our research – 2 major events for our center

- **Recruiting Day** – open house /posters for Industrial Affiliates; Friday before spring classes; January 24, 2020
- **Brooklyn 5G Summit** and NYU WIRELESS annual Board Meeting; April 21-24, 2020

Major value propositions to Industrial Affiliates:
1. Student Resume database
2. Recruiting Day in January
3. Publication database
4. Faculty engagements/videos/secure website for affiliates-only
5. Deep-dive technical collaboration, expertise

Occasional lab tours and impromptu VIP visits
• Industrial Affiliate companies fund our center, gain instant access to all research, and we serve them in all capacities. They provide co-ops and full-time jobs to our students.

• Great experience and contacts for our students, elevates NYU’s reputation in industry.

• These companies support our major proposals and endorse/use our research
Timeless Principles

• No matter how clever wireless engineers are, there will always be demand for improvements
  • greater throughput
  • reduced latency
  • higher reliability
  • more extensive coverage

• You can always lay down more optical fiber; you can never lay down more spectrum!

• Revolutionary developments in wireless communications always occur in the physical layer
  • Marconi (vision: if an electromagnetic signal can cross a room, it could cross an ocean)
  • Fessenden (amplitude modulation)
  • De Forest (three-element vacuum tube)
  • Carson (single side-band)
  • Armstrong (regenerative receiver, super-heterodyne receiver, wide-band frequency modulation)
  • Engel, Frenkkel (cellular telephony)
  • Foschini, Paulraj, … (Multiple-Input/Multiple-Output – MIMO)
Sub-6 GHz spectrum: The most valuable resource in the world!

- FCC AWS-3 spectrum auction, January 2015
  - 65 MHz: 1695-1710 MHz, 1755-1780 MHz, 2155-2180 MHz
  - $41.3 billion net
  - $635/Hz
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• What if FCC could sell 36 GHz of terahertz spectrum for $635/Hz?
  • $22.8 trillion
  • wipe out the national debt!
A new wireless generation begins when base station equipment is introduced into service that is incompatible with previous installed equipment

- 1G: analog (FM)
- 2G: digital
- 3G: spread-spectrum
- 4G: OFDM
- 5G: mmWave and Massive MIMO
- 6G: ???
J.E. Smee (Qualcomm), “Five wireless inventions that define 5G NR – the global 5G standard”

- Scalable OFDM-based air interface
- Flexible slot-based framework
- Advanced channel coding
- Massive MIMO
- Mobile mmWave

- Note:
  - The first three items are only evolutionary, and together could not constitute a new generation
  - Massive MIMO and mmWave are highly disruptive, and are what 5G is all about!
    - unclear, at this time, which will bring greater value
Mobile mmWave


- Increasing the carrier frequency by a factor-of-ten yields 10x available spectrum!

- Issues
  - blockage by walls, foliage, human body
  - wave-length reduced by a factor-of-ten
    - to maintain the same transmitting/receiving area requires 100x ½ wave-length antennas
    - for mobile users, propagation channel changes 10x faster: an increasing fraction of transmission time is spent on learning the channel
Massive MIMO

T.L. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas”, *IEEE Trans. on Wireless Communications, Nov 2010*

- **What is Massive MIMO?**
  - many individually controlled, physically small, low power antennas
  - aggressive spatial multiplexing
  - utilize *measured* channel frequency response for multiplexing/de-multiplexing

- **Benefits**
  - scalability
  - spectral efficiency
  - simplicity
  - great service to all users via simple, effective power control
  - energy efficiency
Antennas transmit the weighted data streams to arrive in-phase at the intended users and out-of-phase elsewhere.
Base station weights and adds received signals for constructive reinforcement of the data stream from each user
Direct Measurement of Channel Response is Essential
FDD Bad! TDD Good!

$M$ base station antennas serve $K$ single-antenna users

TDD: training overhead $\propto K$

| Up Data | $K$ Up Pilots | Down Data |

FDD: training overhead $\propto 2M + K$

| Down Link | $M$ Pilots | Down Data |
| Up Link | $M$ CSI | $K$ Pilots | Up Data |

Mobility limits the number of active users; FDD is a disaster!
Ubiquitous Augmented Reality: Tough Even for Massive MIMO

Horrea Epagathiana, Ostia, Italy

Augmented reality has staggering requirements: 3 Gb/s/user, 10 ms latency

We need a 6th generation!
Wireless Neuro-Sensing: Implantable Inter-Cranial Transmitter


- 100 7.8 kHz neural channels
- ~ 1 Mb/s transmitted in 3.2 – 3.8 GHz spectrum
- How to handle 1000, 10000, … channels?
- Nobody can currently solve this problem!
A. Karalis, J.D. Joannopoulos, M Soljačić, “Efficient wireless non-radiative mid-range energy transfer”, *Annals of Physics, Jan 2008*

- 60 Watts received, at 10 MHz, with 40% efficiency: coupling coefficient ~ .002
- **Could drones and robots be powered wirelessly?**
6G: What will it look like? Will there be a 6th generation?

• Has to be 10x better than 5G

• Needed in 8 – 10 years

• We have no sure-fire physical layer technologies waiting in the wings!
  • eight years ago, mmWave and Massive MIMO already showed considerable promise

• Candidate technologies
  • terahertz
  • cell-free Massive MIMO
  • holographic Massive MIMO
  • super-directive antenna arrays
• Replace a multiplicity of Massive MIMO equipped cells with a single cell comprising randomly located access points

• Advantages over cellular Massive MIMO
  • shadow-fading diversity
  • multiple data streaming to each user possible, even under l.o.s. conditions

Augmented Reality (maybe!): 40 MHz x 10 ant/user x 7.5 bits/s/Hz/ant (23 dB) → 3Gb/s/user
Holographic Massive MIMO
(Large Intelligent Surfaces)

- Replace an array of discrete antennas with a continuous radiating/receiving surface
- Implementation advantages for terahertz operation?
- Is there any fundamental advantage in receiving/controlling the electromagnetic field on a scale smaller than a half-wavelength?
For example, consider a transmitting horn antenna, with an aperture about 10 wavelengths on a side, located in outer space roughly aimed at the earth. With a one wavelength diameter supergain antenna on the earth it is possible to receive virtually all of the power radiated by the horn antenna.  Foschini & Gans, Bell Labs Technical Memo, 1995

- Far removed from all our wireless communication experience and theories

- Spooky action at a distance?
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- Spooky action at a distance?
- No! Old-fashioned Ernst Guillemin network theory + electromagnetic theory
Super-Directivity: $M=8$ Antennas

- Asymptotic super-directive gain: $M^2 = 64$ vs $M = 8$ for maximum-ratio Array Gain Relative to Single-Antenna
Conclusions

- New generations of wireless are predicated on breakthroughs at the physical layer

- 5G has begun
  - physical layer foundations are mmWave and Massive MIMO
  - Massive MIMO will show its greatest value in the most valuable sub-6 Ghz bands
    - preponderance of FDD in USA unfortunately implies that we are stuck with inferior technology

- Exciting new applications will emerge, necessitating new physical layer breakthroughs

- The world will expect a 6th generation of wireless in ~ 8 years
  - nobody is doing sufficient fundamental research
  - possible physical layer breakthroughs, but nothing is sure-fire!
    - Terahertz
    - Cell-Free Massive MIMO
    - Holographic Massive MIMO
    - Super-Directive antenna arrays

Current wireless systems are operating far from any limits imposed by nature!