What is the Role of MIMO in Future Cellular Networks: Massive? Coordinated? mmWave?

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Wireless is Big in Texas

20 Faculty

12 Industrial Affiliates

WNCG provides pre-prints, pre-competitive research ideas, vast expertise, first access to students

Affiliates champion large federal proposals, provide technical input/feedback, unrestricted gift funds

About half of all students intern for an affiliate or work full-time

Affiliates provide real world context

150 Grad Students

Heavily funded center

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Wireless Communications Lab

- Undergrad/grad lab course
  - QAM & OFDM experiments
  - Complete lab manual & software
  - Uses USRP equipment
  - LabVIEW programming

- Complete lab manual available

Outline

- MIMO in cellular networks
- Coordinated Multipoint a.k.a. network MIMO
- Massive MIMO
- Millimeter wave MIMO
- Comparison between technologies
- Parting thoughts
The MIMO Concept

- **MIMO (multiple-input multiple-output) communication channel**
  - Leverages multiple antennas at the transmitter and receiver

- **MIMO is broadly incorporated into wireless systems**
  - Cellular communication, wireless local area networks, ad hoc networks
  - Provides capacity, quality, robustness, resilience to interference

MIMO communication exploits *matrix* propagation channels
Single user MIMO communication

- Send multiple data streams a.k.a. *spatial multiplexing*
- Highest performance requires rich scattering environment
- Incorporated into several commercial wireless systems
- Ex: 8 antennas at the base station and 4 antennas at the mobile station

Multiplexing gains are limited by number of antennas at users
Multiuser MIMO (MU-MIMO)

- Simultaneously send independent data streams to several users
- Multiplexing gains are obtained even with less ideal propagation
- Main obstacles: near-far problem & channel correlation
- Flexibility in user scheduling may overcome the obstacles

Multiplexing gains are limited by number of antennas at base stations
Where is MIMO Headed?

Candidate architectures for 5G

Coordinated MIMO

Massive MIMO

mmWave MIMO
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What is Network MIMO?

- Coordinated transmission from multiple base stations
  - Known as CoMP or Cooperative MIMO or base station coordination
  - Interference turned from *foe* to *friend*
  - Exploits presence of a good backhaul connection
- Used to improve area spectral efficiency, system capacity
Network MIMO Architectures

- Coordinate over backhaul
  - eNodeB to eNodeB
  - Cloud RAN
    - Processing for many base stations using cloud

- Like DAS uses local coordination
  - eNodeB
  - Coordination clusters
  - Dynamic coordination
Potential Gains from Coordination

Throughput gains when out-of-cluster interference is ignored

- More cooperation leads to higher gains
- Cell edge pushed further out, no uncoordinated interference in the cell

Grid model for a cellular network

- 19 cells and 3 sectors per cell
- BS-MS distance = 192 m
- ISD = 500 m

Graph showing sum rates per cell vs. SNR (dB):

- Linear increase
- Unbounded gains

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Addressing Out-of-Cell Interference

- Performance saturates with out-of-cluster interference
- 30% performance gains observed in industrial settings

Be mindful of the saturation point

Critical Issues with Network MIMO

- **Out-of-cell interference**
  - When included, results are not as good

- **Feedback overhead**
  - Need channel state information
  - Performance seriously degrades

- **Control channel overhead**
  - Increased reference signal overhead

- **Backhaul link constraints**
  - Backhaul link latency (delayed CSI and data sharing)

- **Cluster edge effects**
  - Coordination still has a cell edge with fixed clusters
  - Dynamic clustering solves the problem, but more implementation overhead
Network MIMO Conclusions

Observations

- Network MIMO promises a way to get rid of interference
- Yet uncoordinated interference still limits high SNR performance
- Backhaul constraints and system overheads further reduce performance gains
- General disconnect between academia and industry on the potential

Forecast

- Already incorporated into 4G, coordination will be part of 5G as well
- Architectures will evolve to support network MIMO-like coordination
  - Distributed antenna systems are a good starting point
  - Distributed radio access networks are a likely evolution point
  - Cloud radio access networks are a possible end objective
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What is Massive MIMO?

- A very large antenna array at each base station
  - An order of magnitude more antenna elements in conventional systems
- A large number of users are served simultaneously
- An excess of base station (BS) antennas

Essentially multiuser MIMO with lots of base station antennas

Massive MIMO Key Features

- Benefits from the (many) excess antennas
  - Simplified multiuser processing
  - Reduced transmit power
  - Thermal noise and fast fading vanish

- Differences with MU MIMO in conventional cellular systems
  - Time division duplexing used to enable channel estimation
  - Pilot contamination limits performance

Centralized vs. Distributed

7 cells without sectorization
12 users uniformly distributed in each cell
ISD = 500m

Centralized

Distributed

Fixed number of base station antennas per cell

Potential Gains from Massive MIMO

**Uplink**

- 01 cluster
- 03 clusters
- 08 clusters

**Downlink**

- 01 cluster
- 03 clusters
- 08 clusters

7 cells without sectorization, 12 users uniformly distributed in each cell, ISD = 500m

- Distributing antennas achieves higher gains
- Saturation is not observed without huge # of antennas
Critical Issues in Massive MIMO

- Gains are not that big with not-so-many antennas
  - Require many antennas to remove interference
  - Need more coordination to remove effects of pilot contamination

- Massive MIMO seems to be more “uplink driven”
  - Certain important roles are reserved between base stations and users
  - A different layout of control and data channels may be required

- Practical effects are not well investigated
  - Channel aging affects energy-focusing ability of narrow beams
  - Spatial correlation reduces effective DoFs as increasing number of antennas
  - Role of asynchronism in pilot contamination and resulting performance
Massive MIMO Conclusions

Observations

- Pilot contamination is a big deal, but possibly overcome by coordination
- Performance is sensitive to channel aging effects *
- Good performance can be achieved with distributed antennas *
- Not clear how to pack so many microwave antennas on a base station
- Needs more extensive simulation study with realistic system parameters

Forecast

- Massive MIMO will probably not be used in isolation
- Will be combined with distributed antennas or base station coordination
  - Reduces the effects of pilot contamination
  - Work with smaller numbers of antennas

Why mmWave for Cellular?

- **Huge amount of spectrum available in mmWave bands**
  - Cellular systems live with limited microwave spectrum ~ 600MHz
  - 29GHz possibly available in 23GHz, LMDS, 38, 40, 46, 47, 49, and E-band

- **Technology advances make mmWave possible**
  - Silicon-based technology enables low-cost highly-packed mmWave RFIC**
  - Commercial products already available (or soon) for PAN and LAN
  - Already deployed for backhaul in commercial products

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The Need for Gain

- Smaller wavelength means *smaller captured energy* at antenna
  - 3GHz->30GHz gives 20dB extra path loss due to aperture
- Larger bandwidth means *higher noise power* and lower SNR
  - 50MHz -> 500MHz bandwidth gives 10dB extra noise power

Solution: Exploit array gain from large antenna arrays
Antenna Arrays are Important

- Narrow beams are a new feature of mmWave
  - Reduces fading, multi-path, and interference
  - Implemented in analog due to hardware constraints

Arrays will change system design principles
mmWave networks can provide acceptable coverage

- Directional array gain compensates severe path loss
- Smaller beamwidth reduces the effect of interference
Critical Issues in mmWave MIMO

- Dealing with hardware constraints
  - Need a combination of analog and digital beamforming
  - Array geometry may be unknown, may change

- Performance in complex propagation environments
  - Evaluate performance with line-of-sight and blocked signal paths

- Must adapt to frequent blockages and support mobility

- Entire system must support directionality

- Need approval to employ the spectrum
mmWave Conclusions

Observations

- Coverage may be acceptable with the right system configuration
- Strong candidate for higher per-link data rates
- Hardware can leverage insights from 60GHz LAN and PAN
- Highly directional antennas may radically change system design
- Supporting mobility may be a challenge

Forecast

- Will be part of 5G if access to new spectrum becomes viable
- Most likely will co-exist with microwave cellular systems
- Will remain useful for niche applications like backhaul
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Stochastic Geometry for Cellular

Stochastic geometry is a tool for analyzing microwave cellular

- Reasonable fit with real deployments
- Closed form solutions for coverage probability available
- Provides a system-wide performance characterization

Need to incorporate features of each technology

Comparing Different Approaches

- **CoMP model**
  - Sectored cooperation model
  - Typical user can be edge or center user of the cluster
  - Several assumptions made to permit calculation

- **mmWave model**
  - Directional antennas are incorporated as marks of the base station PPP
  - Blockages due to buildings incorporated via random shape theory

- **Massive MIMO model**
  - Analyze asymptotic case with infinite number of antennas at the base station
  - No spatial correlation, includes estimation error, pilot contamination

New expressions derived for each case

SINR Coverage Comparison

Gain from directional antennas and blockages in mmWave

Gain from larger number of antennas

SINR CCDF
Gain from directional antennas and blockages in mmWave

Gain from massive number of antennas

CoMP: $N_t=4$, 2 Users, 3 BSs/Cluster
Massive MIMO: $N_t=\infty$
mmWave: $N_t=64$, $R_c=100m$
SU MIMO: 4X4

Coverage Comparison

Spectrum Efficiency CCDF
Gain from larger bandwidth

Gain from serving multiple users

CoMP: $N_t=4$, 2 Users, 3 BSs/Cluster
Massive MIMO: $N_t=\infty$
mmWave: $N_t=64$, $R_c=100m$
SU MIMO: 4X4

Rate CCDF
# Rate Comparison

<table>
<thead>
<tr>
<th></th>
<th>Massive MIMO</th>
<th>MMwave</th>
<th>CoMP</th>
<th>SU MIMO</th>
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</thead>
<tbody>
<tr>
<td><strong>Signal BW</strong></td>
<td>50 MHz</td>
<td>500 MHz</td>
<td>50 MHz</td>
<td>50 MHz</td>
</tr>
<tr>
<td><strong>User/Cell</strong></td>
<td>8</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>bps/Hz per user</strong></td>
<td>5.47 bps/Hz</td>
<td>8.00 bps/Hz</td>
<td>4.34 bps/Hz</td>
<td>4.95 bps/Hz</td>
</tr>
<tr>
<td><strong>Rate/Cell</strong></td>
<td>21.88 bps/Hz</td>
<td>8.00 bps/Hz</td>
<td>8.68 bps/Hz</td>
<td>4.95 bps/Hz</td>
</tr>
<tr>
<td><strong>Capacity/Cell</strong></td>
<td>1.10 Gbps</td>
<td>4.00 Gbps</td>
<td>434 Mbps</td>
<td>248 Mbps</td>
</tr>
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* mmWave outperforms due to more available BW

* of course various parameters can be further optimized
** SU MIMO is 4x4 w/ zero-forcing receiver
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# Parting Thoughts

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<th>Conclusions</th>
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<tbody>
<tr>
<td>Cooperative MIMO</td>
<td>cooperation will be used in some form, more powerful with better infrastructure, need to be mindful of overheads in system design</td>
</tr>
<tr>
<td>Massive MIMO</td>
<td>some potential for system rates, need large base station arrays, can be used with cooperation</td>
</tr>
<tr>
<td>mmWave MIMO</td>
<td>large potential for peak rates, more hardware challenges, requires more spectrum, more radical system design potential</td>
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Questions?

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